Abstract

The waste from North Carolina's large swine population has led to the degradation of the State's air and water quality, and to adverse effects on human health. The current waste treatment technology, open lagoons with land application, has been banned on new farms in NC since 1997. Ammonia volatilization from these lagoons and during land application, as well as runoff from land application, have overwhelmed the State's eastern region with nitrogen emissions. The State has sought to provide incentives for the development and construction of environmentally superior technologies (ESTs), especially those that generate electricity from the swine waste. We operated a pilot-scale waste treatment system to couple biological nitrogen removal (by nitrification/denitrification) with an existing full-scale anaerobic digestion system to capture methane and produce energy at Butler Farms (Lillington, NC). The nitrogen removal system was able to achieve up to 95% removal of NH_4^+-N and 50% removal of total N from the waste after anaerobic digestion. However, the system did not meet the total nitrogen performance standard of 75% N removal for an EST. Complete denitrification was limited by the availability of biodegradable organic matter in the effluent from the anaerobic digester. We also investigated the potential cost and benefits of coupling nitrogen removal with energy production from swine waste. At full scale, the system would consist of covered anaerobic digesters, a generator, an aerobic nitrification reactor, a denitrification reactor, and a storage basin for the final effluent. At Butler Farms the two existing covered lagoons can be retrofitted to accommodate the proposed integrated system, with a 10-year annualized cost of $148/1000 lb steady-state live weight (SSLW). Annual benefits from energy production, greenhouse gas credits,

renewable energy certificates, and nitrogen credits were also estimated. Including these benefits, the cost of the system would be reduced to \$110/1000 lb SSLW, comparable to the net costs of other potential ESTs.

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1.0 INTRODUCTION

North Carolina is the second largest hog producer in the United States. The North Carolina swine industry supports over 8,000 jobs and generates over $1.9 billion annually *(1)*. Since the 1980s, the industry has experienced tremendous growth, with the most rapid growth occurring in the 1990s. The state hog population increased from 25,000 head in 1980 to 10 million head by 1998 *(2)*. During this time the style of hog farming has mimicked nation-wide trends, transitioning from many small farms to fewer, increasingly larger farms, also referred to as confined animal feeding operations (CAFOs) *(3)*. Despite the tremendous growth of the hog population, the number of North Carolina hog farming facilities has decreased from nearly 70,000 in 1970 to fewer than 5,000 *(1)*. Smithfield Foods, Inc., the largest hog producer in the world, owns an estimated 70 percent of the hogs grown in North Carolina *(4)*.

Waste management at hog farms in North Carolina has become an issue of public concern. Earthen anaerobic lagoons coupled with land application are still the standard waste treatment technology used by growers. There are approximately 4,000 active and 650 inactive swine lagoons in North Carolina *(1)*. Urine and feces from hog barns are flushed into open lagoons of waste where it is degraded by anaerobic microorganisms. Farmers then dispose of the waste and fertilize crops by periodically spraying the lagoon liquid onto fields.

Despite the settling of solid waste and degradation processes that occur in a lagoon, the liquid applied to spray fields has a high nutrient content. These nutrients are primarily in the form of phosphorus and, the nutrient of focus of this study, nitrogen (almost entirely as ammonium, NH_4^+). The nutrients cause eutrophication in nearby water when carried in storm runoff and can lead to elevated nutrient concentrations in groundwater *(5)*. Methane (a potent greenhouse gas), ammonia, hydrogen sulfide and other gases are emitted from lagoons and by volatilization of sprayed lagoon liquid. Ammonia emissions cause respiratory health problems and can result in the deposition of nitrogen into the surrounding environment, while strong odors reduce the value and enjoyment of adjacent properties *(6)*. The lagoon structures themselves can flood or experience catastrophic failure, emitting the waste into the environment and surrounding communities. Even without major structural failure, the North Carolina Department of the Environment and Natural Resources (DENR) found that up to 25% of lined lagoons might leak *(1)*.

Over the past two decades, much work has been done to regulate the environmental impacts of swine farming in North Carolina. Since 1997 the construction of new hog lagoons that do not utilize innovative technologies has been banned. The North Carolina attorney general has worked with leading hog-producing corporations and local universities to develop new waste treatment technologies with the ultimate goal of phasing out the use of lagoons. The state hopes to find a technology that meets new environmental performance standards while remaining technically and economically feasible.

This project sought to explore a proposed technology for hog waste treatment that combines the capture of methane for energy production with biological nitrogen (N) removal. A pilot-scale N removal system was operated at a farm with an existing methane capture system and the results were used to design a full-scale biological N-removal system. The system's performance, costs, and economic benefits were assessed and compared to other proposed technologies.

2.0 Background

2.1 History of North Carolina Swine Farm Legislation

The rapid increase in the hog population and prevalence of CAFOs in North Carolina was aided by 1991 state legislation that exempts large-scale hog farms from local zoning regulations *(7)*. The first major environmental legislation specific to the swine industry came in 1995, when the General Assembly passed a law requiring that land application be done by a certified operator *(8)*, a law establishing the permitting and monitoring regulations for animal waste management systems, a state price-sharing system for waste management innovation *(8, 9)*, and the Swine Farm Siting Act. This legislation prevented swine houses and lagoons from being constructed near occupied residences (1,500 ft); schools, hospitals, and churches (2,500 ft); or property boundaries (500 ft) to reduce the odor's impact on adjoining properties *(10)*. On June 21, 1995, a lagoon at Ocean View Farms in Onslow County, NC failed, sending 22 million gallons of raw hog waste into New River tributaries. The spill caused a massive fish kill and spurred a series of environmental regulations for the hog industry *(11)*. The 1997 Clean Water Responsibility Act placed a moratorium on the expansion of existing large hog farms and the construction of new farms in North Carolina with more than 250 hogs *(12)*. This act was meant to prevent the construction of new lagoons until further regulations could be established and, ultimately, until new waste treatment technologies could be developed. The moratorium was renewed in 1998, 1999, 2003, and again in 2007 *(13-15)*. In 1999, flooding from Hurricane Floyd caused the overflow of numerous hog lagoons, contaminating local water supplies and gaining the attention of the national press *(2)*.

The moratorium renewal legislation permitted new swine waste management systems to be constructed only if they met a series of performance standards. These standards sought to:

1. Eliminate the discharge of animal waste to surface waters and groundwater through direct discharge, seepage or runoff;
2. Substantially eliminate atmospheric emissions of ammonia;
3. Substantially eliminate the emission of odor that is detectable beyond the boundaries of the parcel or tract of land on which the swine farm is located;
4. Substantially eliminate the release of disease-transmitting vectors and airborne pathogens; and
5. Substantially eliminate nutrient and heavy metal contamination of soil and groundwater.

The North Carolina Administrative Code (Title 15A, Chapter 2, Sub Chapter T .1307) stipulates that groundwater and surface water goals will be met through proper storage and treatment structure design (in accordance with NRCS standards); ammonia emission goals will be met by setting limits on the quantity of ammonia emitted by a farm; odor performance standards are met by setting limits on the measured and observed odor intensity in accordance with ASTM standards; disease and pathogen-related performance standards will be met by limiting fecal coliform concentrations of the system effluent; and nutrient and heavy metal goals will be met by meeting NRCS Comprehensive Nutrient Management Plan (CNMP) guidelines. Combined ammonia emissions from swine waste treatment and storage structures may not exceed an annual average of 0.2 kg NH_3-N/wk/1,000 kg steady state live weight (SSLW), ammonia emissions from land application sites may not exceed an annual average of 0.2 kg NH_3-N/wk/1,000 kg SSLW, and ammonia emissions from the swine farm may not exceed an annual average of 0.9 kg NH_3-N/wk/1,000 kg SSLW *(102)*.

In 2000, the Attorney General of North Carolina entered into an agreement with Smithfield Foods and Premium Standard Farms (PSF), two of the largest farming corporations in the state and nation, to fund the development and implementation of environmentally superior technologies (ESTs) for hog waste management *(16)*. This agreement became known as the Smithfield Agreement and stated that the companies would agree to:

> (1) undertake immediate measures for enhanced environmental protection on Company-owned Farms and provide assistance to Contract Farmers in undertaking these same measures; (2) commit $15 million for the development of Environmentally Superior Technologies for the management of swine waste and to facilitate the development, testing, and evaluation of potential technologies on Company-owned Farms; (3) install Environmentally Superior Technologies on each Company-owned Farm in North Carolina and provide financial and technical assistance to Contract Farmers for the installation of these technologies; (4) commit $50 million of environmental enhancement activities; (5) cooperate fully with the Attorney General to ensure compliance with applicable laws, regulations, policies and standards; and (6) in cooperation with the Attorney General and all other interested parties, take a leadership role in enhancing the effectiveness of the Albemarle-Pamlico National Estuary Program.

In their agreement, Premium Standard Farms was asked to pay $2.1 million. In 2002, Frontline Farmers also joined the agreement, though they were not required to pay for EST development. Eighteen EST candidates were identified, developed and evaluated *(17)*. The Smithfield Agreement defines ESTs as any technology, or combination of technologies that (1) is permittable by the appropriate governmental authority; (2) is determined to be technically, operationally and economically feasible for an identified category or categories of farms as described in the agreement and (3) meets the five North Carolina performance standards listed above. These environmental performance standards were quantified as follows for the purposes of the Smithfield Agreement: zero discharge of waste to surface and groundwater; an 80% reduction in ammonia emissions; odor intensity levels of no more than two (on a scale of zero to ten) at the property boundary; a 99.9% reduction in pathogens; a 75% reduction in total nitrogen emission; and a 50% reduction in total phosphorus, copper and zinc emissions *(15)*. These performance standards differ from the state regulations identified above. When the agreement-funded investigation ended in 2006, none of the 18 candidate EST technologies were found to be economically feasible for existing swine farms, but five of the technologies were found to be economically feasible for new swine farms (the agreement states that for technologies to be accepted and implemented they must be economically feasible on existing farms). The Attorney General and Smithfield Farms currently disagree whether the agreement still holds and whether the company would be required to implement an EST on its farms if a feasible technology were found *(17)*.

In 2007 the General Assembly established a program to assist farmers in financing innovative animal waste management systems and established a swine farm methane capture pilot program *(15)*. Also in 2007, the state passed a law to promote the development of renewable energy technology. The law states that 3% of retail electricity sales should come from renewable sources by 2012, 6% by 2015, 10% by 2018, and 12.5% by 2021. Of state retail electricity sales, 0.07% must come from swine waste resources by 2012, 0.14% by 2015, and 0.20% by 2018 *(18)*. The methane capture pilot program hoped to begin the development of energy production from North Carolina's swine waste to meet these energy goals.

2.2 Waste Treatment Methods

The Smithfield Agreement resulted in the identification of 18 potential ESTs and investigated their environmental benefits and economic feasibility. Fourteen of the 18 proposed ESTs are summarized in Table 1.

Table 1 - Potential ESTs investigated under the Smithfield Agreement. Costs displayed as $(2004)/1000 lb SSLW when normalized to a 8,800-head feeder to finish farm *(19-21)*.

Technology	Description	Cost ($/1000 lbs. of SSLW)
Super Soils System USA	Solids are separated from waste using a flocculating agent and solids are sent off-site to be used for a value-added product. Liquid waste circulates between nitrification and denitrification tanks to remove nitrogen before the pH is raised to remove phosphorus and kill viruses and bacteria.	$255.57
Organic Biotechnologies, LLC (ORBIT) High Solids Anaerobic Digester	An enclosed high-temperature, high-solids anaerobic digester converts the solid portion of the waste stream to biogas for energy production. This system was coupled with the Super Solids technology and remaining solids were used for a value-added product by the Super Solids technology.	$551.24
Ambient Temperature Anaerobic Digester and Greenhouse for Swine Waste Treatment and Bioresource Recovery at Barham Farm	A covered, in-ground anaerobic digester produces biogas for energy production. Excess heat from energy production is used to heat on-site greenhouses. Liquid flows to a secondary lagoon and nitrification tanks before being routed through the greenhouses. Crops in the greenhouses remove nutrients from the waste prior to land application.	$94.91
Solids Separation - Reciprocating Wetlands	Solids are removed in a settling tank before liquid enters wetland cells. The cells alternate between anaerobic and aerobic conditions to promote nitrogen removal through nitrification/denitrification.	$144.34

Table 1 (continued) - Potential ESTs investigated under the Smithfield Agreement. Costs displayed as \$(2004)/1000 lb SSLW when normalized to a 8,800-head feeder to finish farm *(19-21)*.

Technology	Description	Cost (\$/1000 lbs. of SSLW)
Ekokan Upflow Biofilter	Solids are separated from waste using a screen separator. Liquid passes through 1st and 2nd stage aerated biofilters to remove nutrients. Biofilter tanks are full of plastic fixed media covered in biofilm.	\$303.86
Belt System for Manure Removal	A slanted conveyor belt below swine pens allows for the separation of hog urine and feces. The belt collects the solid waste which is then used for the solider fly project.	\$89.33
Belt Manure Removal and Gasification System to Convert Dry Manure Thermally to a Combustible Gas Stream for Liquid Fuel Recovery	Solid and liquid waste is separated using a slanted conveyor belt below swine pens. The solids are burned in a low-oxygen environment to produce biogas which will be used to make fuel-grade ethanol. The ash remaining from gasification is used as a value-added feed supplement. The liquid waste is treated in a sequencing batch reactor.	\$85.90
Solids Separation/Combustion for Energy and Ash Recovery	Solids were separated using a combined screw press and tangential flow settling tank method and a screen and hydraulic screw press system at different sections of the farm. Solids were transported to Idaho where they were combusted experimentally and the resulting ash was studied for its fertilizer value.	\$115.98
Solids Separation/Constructed Wetlands System	Solids are separated from the waste stream using a screen before the liquid flows through a constructed wetlands. Nitrogen is removed biologically by microbes in the root zone of wetland plants. The liquid enters an irrigation pond prior to land application. The solids removed are available as a potential value-added product for off-site use.	\$136.74
Sequencing Batch Reactor (SBR)	Waste enters a homogenization tank before being pumped into a SBR once a day. The reactor cycled between aerobic conditions (to promote nitrification) and anoxic conditions (to promote denitrification).	\$221.16

Table 1 (continued) - Potential ESTs investigated under the Smithfield Agreement. Costs displayed as \$(2004)/1000 lb SSLW when normalized to a 8,800-head feeder to finish farm *(19-21)*.

Technology	Description	Cost (\$/1000 lbs. of SSLW)
Manure Solids Conversion to Insect Biomass (Black Soldier Fly Project)	Solid waste recovered from the waste stream is placed in shallow concrete pits where black soldier fly larvae feed on the manure and reduce its mass. The larvae turn to prepupae and climb up the sloped walls of the pits, fall into a gutter, and crawl to a disposal pail.	-
ISSUES (Innovative Sustainable Systems Utilizing Economical Solutions) - RENEW (Recycling of Nutrient, Energy and Water) System	Liquid is thickened before entering a mesophilic, covered digester where biogas is produced for energy production. The liquid flows to a polishing tank and then to an aerobic nitrification pond. A portion of the effluent is used for flushing barns and a portion is filtered and subjected to reverse osmossis before being used as hog drinking water.	\$95.45
ISSUES - Permeable Lagoon Cover	Waste enters an anaerobic lagoon covered with a permeable cover that reduces odor and ammonia emissions. Liquid then enters an aerated nitrification pond and then a denitrification pond. Liquid from the denitrification pond is used for land application and flushing the hog barns.	\$98.75
ISSUES - Aerobic Blanket	Waste enters an anaerobic lagoon that is "covered" with a spray of aerated water to reduce odor and ammonia emissions. Liquid then flows into an aerated nitrification pond and a denitrification pond. Liquid in the denitrification pond is used for land application and for flushing the hog barns.	\$65.81

The Barham Farm and Super Soils technologies are most similar to the technology investigated in this report due to their methane capture system and a nitrogen removal system, respectively.

When the five-year study was completed in 2006, the Super Soils system was found to be feasible for liquid waste treatment and the Super Soils composting technology, gasification, the BEST technology, and the ORBIT technology were found feasible for solid waste treatment. Most technologies investigated included a solids separation component *(21)*.

2.3 Relevant Biological Processes

The system investigated in this report seeks primarily to reduce methane, ammonia and total nitrogen emissions through anaerobic digestion, biological nitrification and biological denitrification. These processes are used widely in the treatment of municipal wastewater.

Methane (CH_4), along with carbon dioxide (CO_2), water and trace gases, are produced in the anaerobic lagoon during the biological degradation of the waste's organic matter. Anaerobic digestion is a four-step process consisting of: hydrolysis, the degradation of carbohydrates, fats and proteins (organic matter) to sugars, fatty acids and amino acids; acidogenesis, the degradation of the hydrolysis end products to volatile fatty acids, alcohols, hydrogen, carbon dioxide and ammonia; acetogenesis, the degradation of alcohols and higher-molecule-weight fatty acids to acetic acid, hydrogen and carbon dioxide; and methanogenesis, where the proceeding intermediate products are converted to methane and carbon dioxide *(22)*. Stoichiometrically, each kg of organic matter (measured as chemical oxygen demand, COD) is expected to produce 0.25 kg methane.

Nitrification is a two-step process that consists of the oxidation of ammonium to nitrite and the oxidation of nitrite to nitrate:

Ammonium Oxidation: $NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+$

Nitrite Oxidation: $NO_2^- + 0.5O_2 \rightarrow NO_3^-$

Net Reaction: $NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$

Autotrophic bacteria are responsible for both steps of nitrification *(22)*. Each kg of NH_4^+-N requires 4.57 kg of O_2 for complete nitrification. The H^+ produced during the reaction consumes alkalinity present in the waste. An alkalinity ratio of 2 mole HCO_3^-/mole NH_4^+-N is required to buffer the complete nitrification reaction (7.14 kg alkalinity as $CaCO_3$ per kg NH_4^+-N). Too little alkalinity will lower the pH in the nitrifying environment and inhibit nitrifying bacteria. Nitrifying bacteria favor environments with a neutral pH *(23)*. Previous studies have found that the alkalinity in a given lagoon may or may not meet the stoichiometric alkalinity demands of nitrification, but those that do not meet the demand are close to doing so. Alkalinity is produced during denitrification, such that a system that circulates the waste between nitrifying and denitrifying environments, such as the system investigated in this report, has a greater chance of meeting the alkalinity demands required during nitrification. The goal of the nitrification of animal waste is to remove NH_4^+, which would preclude volatilization of NH_3 during storage and land application.

During denitrification, heterotrophic microorganisms consume nitrate and organic matter (COD) to produce carbon dioxide, water, nitrogen (N_2) and alkalinity:

$$\text{Denitrification: Organic Matter} + NO_3^- \rightarrow CO_2 + H_2O + N_2 + OH^-$$

Not shown are the intermediate phases as nitrate is converted to nitrogen gas: nitric oxide (NO) and nitrous oxide (N_2O) *(22)*. N_2O is a potent greenhouse gas *(24)* and NO contributes to the destruction of stratospheric ozone *(25)*, while N_2 makes up 78% of the atmosphere and is harmless *(22)*. The goal of biological denitrification is to reduce the total nitrogen (TN) by removing the nitrate produced in the nitrification process. Biological denitrification requires an anoxic environment with a dissolved oxygen (DO) concentration less than 0.1 mg/L *(26)*. Approximately 2.86 kg of biodegradable COD are consumed during the reduction of 1 kg of nitrate. In addition to nitrate reduction, COD is also consumed by the microorganisms during cell synthesis. Denitrification produces approximately 3.75 kg alkalinity (as $CaCO_3$) per kg of nitrate reduced – roughly one-half the amount of alkalinity that is consumed during nitrification. Like nitrifying bacteria, denitrifying bacteria prefer an environment with a neutral pH, although denitrifying bacteria species can tolerate a wider variation (pH 5.0-8.0) before denitrification rates are reduced *(22)*.

The primary concern of coupling anaerobic digestion with a biological nitrification/denitrification system is that too little biodegradable COD will remain in the waste after digestion to allow for complete denitrification. The ratio of TN and biodegradable COD in the anaerobic digester effluent determines whether complete denitrification can occur. Assuming that the TN in the effluent of the anaerobic digester was only in the form of NH_4^+ and that complete nitrification occurs, the biodegradable COD concentration in the anaerobic digester effluent must be at least 2.9 times the TN concentration for complete denitrification to occur. Not all COD produced in hog waste is biodegradable, and 35% to 70% *(27-30)* of the biodegradable COD produced is consumed during anaerobic digestion. Though limited literature exists measuring the TN and COD of anaerobic digestion effluent, some studies have found adequate COD concentrations in anaerobic digestion effluent *(28, 31, 32)* while others have not *(27, 29, 30, 33-36)*. Of those that found the anaerobic digestion effluent to have an in adequate COD concentration for total denitrification, the COD concentration was high enough to reduce a significant fraction of the TN.

3.0 Butler Farm Operation and Waste Characterization

3.1 Butler Farm Operation

Butler Farm is a swine farm located in the Cape Fear River Basin near Lillington in Harnett County, North Carolina. The approximately 8,000-head farm operates as a grow/finish farm under contract with Prestage Farms. The farm uses a lagoon and spray field system to manage its animal waste. Operation began in 1995 with six barns and one lagoon; in 1997 an additional four barns and a second lagoon began operation *(37)*.

A pull-plug pit system is used to collect waste and flush it from the barns. Under each barn is a 40,000-gallon pit which is filled weekly with liquid from a lagoon. Waste collects in the pit and after one week the full volume of the pit is emptied into a lagoon. Barns 1-6 are emptied into and filled from Lagoon 1 and barns 7-10 are emptied into and filled from Lagoon 2 as shown in Figure 1. For barns 1-6, the liquid in barn one is changed every Monday, barn two every Tuesday, etc. In barns 7-10, the liquid in one barn in changed every other day (barn 7 on Monday, barn 8 on Wednesday, barn 9 on Friday, barn 10 on Sunday, barn 7 on Tuesday, etc.). No more than one barn is flushed into each of the lagoons on any given day *(37)*.

Figure 1 - Aerial view of Butler Farm barns and lagoons. (from Google Maps)

Butler Farm is participating in a project to evaluate potential carbon credits from capturing methane on hog farms with Environmental Credit Corp. In 2008, plastic covers and a methane capture and monitoring system were installed on the lagoons *(37)*. The 60mm HDPE covers sit on the surface of the lagoon liquid to minimize headspace volume *(38)*. Pipes run throughout the cover to collect the biogas produced and transport it to a flare. Since July, 2008 the methane from the lagoons has been captured, measured, and burned *(37)*. The installation of the covers converted the lagoons to anaerobic digesters. For the purposes of this report, these digesters will continue to be referred to as lagoons. Neither lagoon is mixed, except as may occur during the discharge of barn flush or withdrawal from the lagoon for spraying.

3.2 Butler Farm Waste Characterization

As is typical of North Carolina swine farms, waste entering the waste management system on Butler Farms is a combination of urine, feces, waste drinking water and fresh water used periodically to wash the barns (such washing is distinct from routine flushing of the pits). Nitrogen is present in the waste in both organic and inorganic forms. Virtually all inorganic nitrogen entering the waste management system is in the form of ammonium (NH_4^+), which is produced by the hydrolysis of the urea in urine *(39, 40)*. Prior to the installation of the lagoon covers, the ammonium concentration in the lagoons at Butler Farms was 400-1000 mg NH_4^+-N/L *(41-43)*. This concentration range is consistent with the highly variable concentrations reported in the literature, which indicated that uncovered finishing farm swine lagoons have ammonium concentrations of 100-3,700 mg NH_4^+-N/L *(44-46)*. After installation of the lagoon covers, the ammonium concentration steadily increased to approximately 2,200-2,400 mg NH_4^+-N/L *(41)*. The lagoon covers prevent ammonia from volatilizing and escaping into the atmosphere, increasing the concentration of ammonium in the lagoons.

During this study the ammonium, total nitrogen, COD, solids concentration, pH, alkalinity, and temperature of the lagoon liquid (in Lagoon 1) were routinely monitored. Samples from the lagoon were obtained over the period September 10, 2010 through May 27, 2011. These data are summarized in Table 2.

Table 2 - Lagoon liquid characteristics 9/10/10 through 5/27/11.[a]

Item	Value	N
NH_4^+-N (mg/L)	2,340 ± 151	88
TN (mg/L)	2,740 ± 168	51
Total COD (mg/L)	7,520 ± 2,260	37
Soluble COD (mg/L)	5,310 ± 1,800	36
TSS (mg/L)	1,560 ± 236	24
VSS/TSS	0.40 ± 0.04	15
pH	7.71 ± 0.23	27
Total Alkalinity (mg/L as $CaCO_3$)	12,200 ± 415	27
Bicarbonate Alkalinity (mg/L as $CaCO_3$)	10,600 ± 460	27

[a] Data are means and standard deviations; all values are rounded to three significant figures.

There was considerable seasonal variability in the temperature of the lagoon, with summer temperatures as high as 34.8°C and winter temperatures as low as 5.1°C. COD concentrations also varied by season, increasing in the colder winter months (Figure 2). Note that the data shown in Figure 2 and in many subsequent plots are based on 30-day running averages. The 30-day running average was chosen to help smooth inherent day-to-day variability, and is consistent with the long storage times in the lagoon (and retention time for the proposed nitrogen removal system).

The increased COD during cold weather corresponded to a reduction in gas production in Lagoon 1 (data not shown), presumably due to reduced rates of methanogenesis. When lagoon temperatures warmed to approximately 15°C in the spring, the consumption of organic matter in the lagoon increased and the COD concentrations decreased. This is consistent with previous studies that found microorganisms typically involved in animal waste degradation to be inhibited and methane production reduced at low temperatures *(47, 48)*.

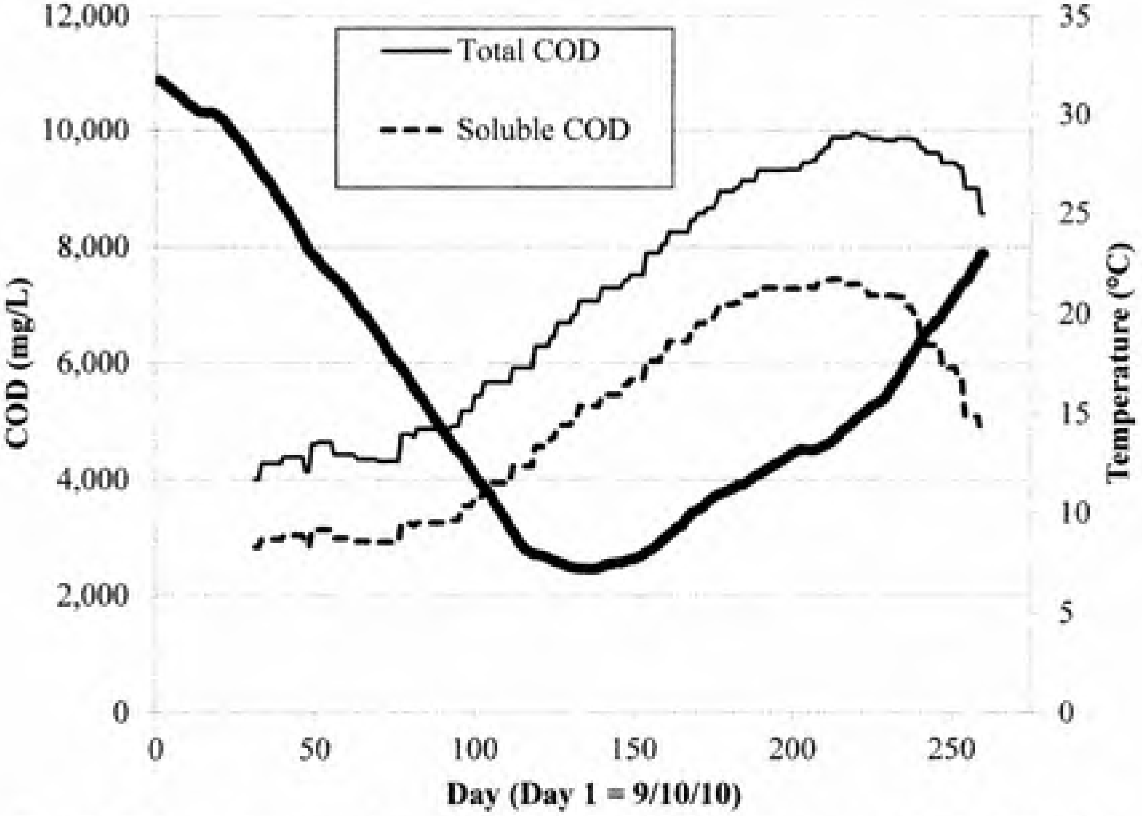

Figure 2 - 30-day running average lagoon temperature and 30-day running average total and soluble COD in lagoon effluent.

Total COD concentrations ranged from approximately 2,000 to 10,000 mg/L and soluble COD concentration ranged from approximately 1,500 to 7,500 mg/L. Typical uncovered anaerobic lagoons have total COD concentrations of 600-4,000 mg/L *(27-30, 33)*. The ratio of total COD to NH_4^+ (mg/L total COD divided by mg/L NH_4^+-N for a given sample day) ranged from 0.85 to 4.27, indicating that during a portion of the year, enough COD remains in the lagoon effluent for complete denitrification (as indicated above, a ratio of at least 2.9 is required). Given a lagoon effluent concentration of 2,340 mg NH_4^+-N/L, the system will require at least 6,790 mg/L COD for complete denitrification. At full scale, the lagoon should be heated to reduce variability in temperature, COD consumption, and methane production.

4.0 Integrated Methane Capture and Biological Nitrogen Removal System

The concept evaluated in the study is to first treat hog waste by anaerobic digestion for methane capture and energy recovery, then biologically treat the digested liquid to remove ammonium and, ideally, total nitrogen. The integrated system is proposed to operate in this order because the biological removal of ammonium requires aeration of the waste. If aeration were to be implemented before anaerobic digestion, then much of the organic matter in the waste could be oxidized incidentally, thereby increasing oxygen consumption (with a corresponding increase in cost) and reducing the amount of organic matter available for conversion to methane.

In the proposed integrated system, there are various options for flushing waste from the barns. These options are described in detail in Section 5. To illustrate the overall concept, the option selected for further evaluation is shown schematically in Figure 3.

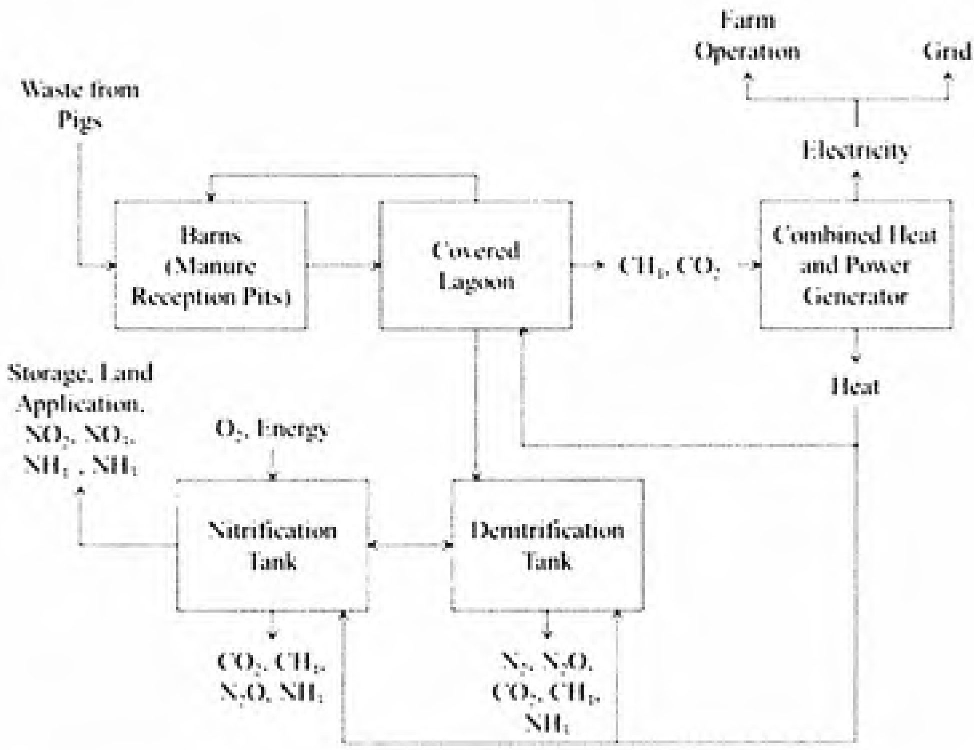

Figure 3 – A proposed scheme for a full-scale integrated system for energy production and nitrogen removal.

In the methane capture component of the system, waste from the swine barns would enter a covered anaerobic lagoon via pull-plug pits that are flushed every six to seven days. In the lagoon, microorganisms will digest the organic matter in the swine excrement and convert it to methane, carbon dioxide, and other gasses that make up the collected biogas. Instead of being burned by a flare (as is current practice at Butler Farms), the biogas would be combusted in a combined heat and power generator-engine set. Electricity produced would be used for on-site farm operations with any surplus electricity sold to the local power utility. Excess heat from combustion would be used to heat the nitrification tank, denitrification tank, and lagoon.

Three schemes were explored for the biological nitrogen removal system. Each biological nitrogen removal system investigated couples an aerobic nitrification tank (N tank) with an anoxic denitrification tank (D tank). At full scale, lagoon effluent would enter the denitrification tank and be recycled between the nitrification tank and the denitrification tank, which is a common approach for nitrogen removal used in municipal wastewater treatment *(22)*. The three schemes vary in the source used to flush the barns and in handling the final (nitrified) effluent. The scheme shown in Figure 3 was chosen as the optimal scheme for Butler Farms and is used throughout this report when reporting expected full-scale performance, costs and benefits.

4.1 Pilot Scale Operation

A pilot-scale biological nitrification/denitrification (N/D) system was operated at Butler Farms from July 31, 2010 to May 27, 2011. The system consisted of sealed, high-density polyethylene (HDPE) nitrification and denitrification tanks and was housed in a trailer that was placed on the berm at the edge of Lagoon 1 (the edge furthest from the barns; see Figure 1). The trailer was cooled and heated to maintain a constant indoor temperature of approximately 20-25° C. Temperature control of the trailer was able to maintain relatively constant temperatures in the nitrification and denitrification tanks despite a highly varied lagoon temperature. The nitrification tank had an average temperature of 23.3° C and the denitrification tank had an average temperature of 21.3°C. Thirty-day running averages of lagoon, N tank, D tank and trailer temperatures are shown in Figure 4.

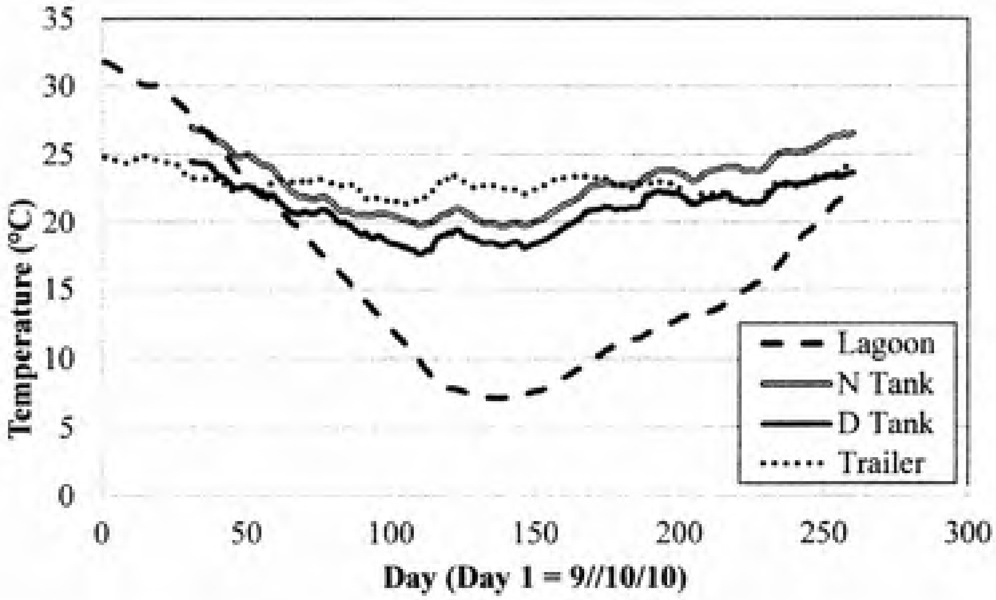

Figure 4 - 30-day running average of Lagoon 1, N Tank, D Tank and trailer temperatures 9/10/10 through 5/27/11.

The system was started by mixing nitrifying activated sludge from the Orange Water and Sewer Authority (OWASA) activated sludge system with tap water in the nitrification tank. To account for startup and some initial operational problems, only data collected between September 10, 2010 and May 27, 2011 are used to determine typical flow rates, reactor performance and subsequent full-scale design.

From September 10, 2010 to February 9, 2010, the N/D system was operated with a target denitrification tank (D tank) volume of 500 L throughout the project and a target nitrification tank (N tank) volume of 2000 L. From February 10, 2011 to May 27, 2011, the target volume of the N tank was 2500 L. For the purposes of this report, September 10, 2010 through February 9, 2011 is called Period 1 and February 10, 2011 through May 27, 2011 referred to as Period 2. The actual tank volumes during these periods are shown in Table 3. Pump flow rates and liquid volumes in the N and D tanks were monitored daily. Throughout the project the influent flow rate from Lagoon 1 to the D tank remained constant with an average flow rate of 42 ml/min. This corresponds to a system hydraulic retention time (HRT) of 33.1 days for Period 1 and 41.3 days for Period 2 (Table 3). Liquid from the D tank was pumped to the N tank at an average rate of 143 ml/min and liquid from the N tank was recycled to the D tank at an average rate of 114 ml/min, resulting in an internal recycle ratio of 2.8. Liquid was pumped from the nitrification tank back into the lagoon at an average rate of 42 ml/min. The corresponding HRT in the N tank was 24.8 days in Period 1 and 33.1 days in Period 1. The HRT in the D tank was 8.3 days in Periods 1 and 2 (Table 3).

Table 3 – Average pilot-scale liquid flow rates, volumes, and flow parameters.

Parameter	Value
Lagoon to D Tank	42 ml/min
D Tank to N Tank	143 ml/min
N Tank to D Tank	114 ml/min
N Tank Effluent	42 ml/min
Period 1 N Tank Volume	1553 L
Period 1 D Tank Volume	521 L
Period 2 N Tank Volume	1995 L
Period 2 D Tank Volume	533 L
Period 1 System HRT	33.1 days
Period 2 System HRT	41.3 days
Internal Recycle Ratio	2.8

The nitrification tank was aerated using pure oxygen and a fine bubble diffuser, and was mixed using a submersible pump. Oxygen was pumped into the nitrification tank at a typical rate of 0.65 L/min (at ambient temperature) to maintain a target dissolved oxygen (DO) concentration of at least 5.0 mg/L. The DO concentration was monitored continuously with a probe inserted into a recirculation line in the N tank, which was also used to draw samples for other analyses. The typical O_2 flow rate of 0.65 L/min does not reflect the very high (1.6 L/min) or very low (0.2 L/min) oxygen flow rates that were very occasionally used before discovering maintenance issues with the DO probe (e.g., biological build-up or a bubble surrounding the probe). These problems caused dramatic swings in the measured DO. A summary of events during reactor operation can be found in Appendix A.

The pH in the nitrification and denitrification tanks was continuously monitored, and alkalinity in each of the tanks was measured weekly. When the pH in the nitrification tank fell below 6.8, a concentrated sodium carbonate (Na_2CO_3) solution was automatically pumped into the nitrification tank. Although the pH in the tanks was measured continuously, only a single manual pH reading each day was recorded. The pH and alkalinity of the lagoon effluent were measured weekly to bi-weekly. Thirty-day running averages of N and D tank pH and discrete lagoon pH measurements from samples are shown in Figure 5.

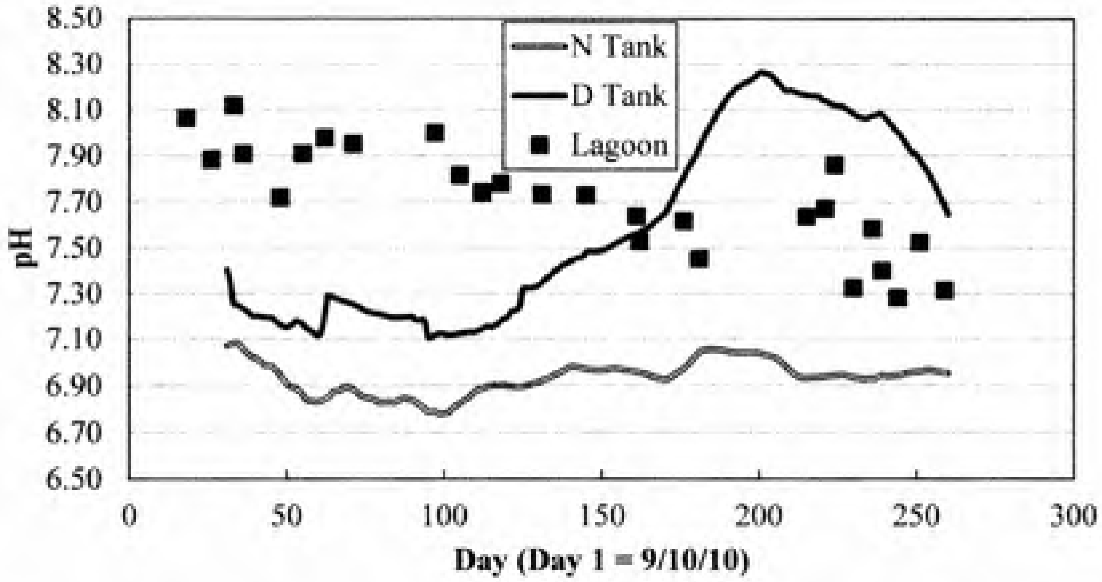

Figure 5 - 30-day running average of N and D tank pH, and discrete pH values in lagoon effluent, 9/10/10 through 5/27/11.

Between September 10, 2010 and May 27, 2011, 120 lb. (55 kg) of sodium carbonate were pumped into the N tank to buffer the nitrification reaction (see Appendix A for a summary of events during reactor operation). The increase in D tank pH corresponds to the seasonal increase in lagoon effluent COD and an increase in alkalinity-producing denitrification.

4.2 Pilot Scale Results and Performance

Liquid samples were collected three times a week from the lagoon effluent, the N tank and the D tank over the duration of the project. These samples were used to measure ammonium, nitrite, nitrate, TN, total dissolved nitrogen (TDN), and COD concentrations in the lagoon (Table 2) and in the reactors (Table 4). While the ammonium, nitrite, and nitrate concentrations were measured three times a week for the N and D tanks, the lagoon effluent was only measured for ammonium. All inorganic nitrogen in the lagoon was assumed to be in the form of ammonium. TN and TDN were measured three times a week between November 22, 2010 and April 6, 2011 in the lagoon effluent, N tank and D tank. COD was measured twice a week and alkalinity, total suspended solids (TSS) and volatile suspended solids (VSS) were measured once a week. Temperature in the lagoon, N tank and D tank as well as pH in the N and D tanks was measured continuously and recorded once per day.

Table 4 - Average pilot scale parameter measurements between 9/10/2010 and 5/27/2011.[a]

Parameter	Nitrification Tank (System Effluent)		Denitrification Tank	
	Value	N	Value	N
NH_4^+-N (mg/L)	156 ± 141	99	700 ± 307	98
TN (mg/L)	979 ± 209	53	1178 ± 304	53
TDN (mg/L)	1007 ± 250	52	1151 ± 281	52
NO_2^--N (mg/L)	412 ± 239	99	133 ± 187	99
NO_3^--N (mg/L)	464 ± 379	99	249 ± 250	99
Total COD (mg/L)	2721 ± 766	64	2855 ± 564	67
Soluble COD (mg/L)	1943 ± 592	68	2039 ± 403	69
TSS (mg/L)	1246 ± 628	27	982 ± 223	27
VSS/TSS	0.41 ± 0.05	15	0.47 ± 0.05	15
pH	6.94 ± 0.15	256	7.57 ± 0.49	254
Total Alkalinity (mg/L as $CaCO_3$)	3213 ± 1373	27	6378 ± 1993	27
Bicarbonate Alkalinity (mg/L as $CaCO_3$)	2412 ± 1170	27	5476 ± 1898	27

[a] All values are means and standard deviations, rounded to three significant figures.

The concentrations of nitrogen species were highly variable throughout the operation of the pilot scale system, in part due to the operating errors that caused losses in performance. Thirty-day running averages of nitrogen species in the lagoon effluent, N tank and D tank are shown in Appendix B. The ammonium concentration in the lagoon effluent remained consistently between 2,200 and 2,400 mg/L throughout the project. Ammonium-N concentrations in the D and N tanks were typically 500 to 800 mg/L and from below quantification limits to 250 mg/L, respectively. Figure 6 shows the percent ammonium removal of the system (the difference between the lagoon effluent ammonium concentration and the N tank ammonium concentration) and the 30-day running average of those values.

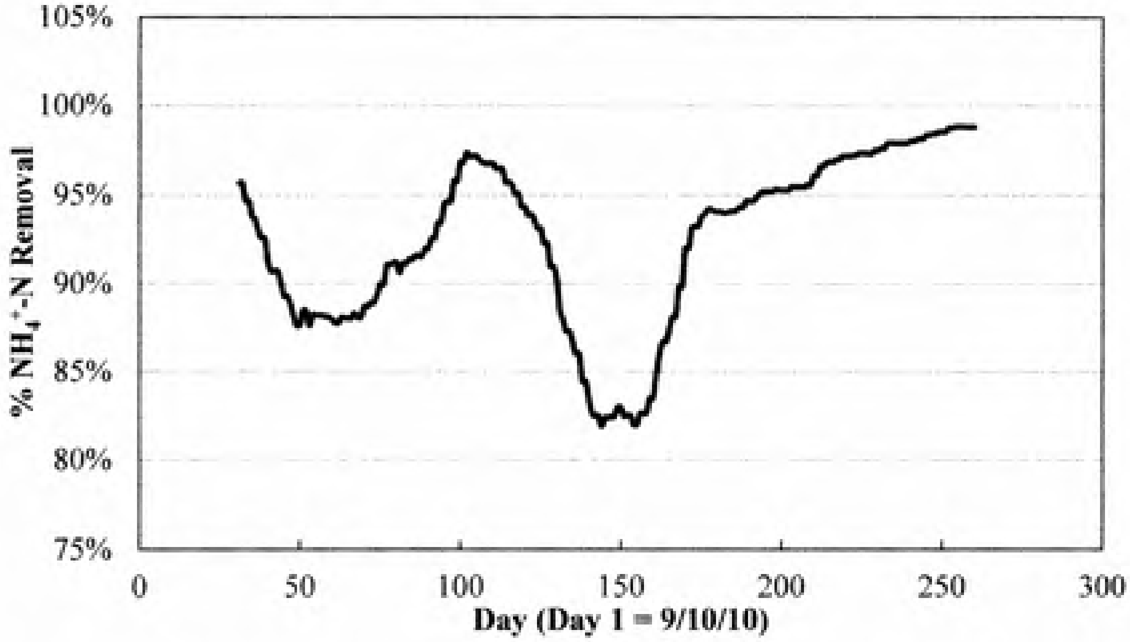

Figure 6 - Percent ammonium removal (30-day running average). Percent value was calculated by looking at the difference between ammonium concentrations in the influent (lagoon effluent) and effluent (N tank) on a given day.

The decline in performance from mid-December to the end of January illustrated in Figure 6 was due to an operating error in which the pumping directions between the N and D tanks were inadvertently switched (see Appendix A). As shown in Figure 6, it took approximately three months to return to the ammonium removal rates observed prior to the operating error.

Reduced rates of ammonium removal may have also been a result of seasonal variation in the lagoon liquid. Also during this time, we did not observe complete nitrification in the N tank. Nitrite began to accumulate in the N tank and less nitrate was produced (see Appendix B, Figure B2). Despite operation difficulties and potential seasonal variability, the pilot-scale system maintained an ammonium removal rate greater than 80%, the required ammonia emissions reductions required for Smithfield Agreement ESTs *(15)*. The system frequently achieved ammonium reductions greater than 95%. The pilot-scale system was able to achieve a TN removal between 55% and 75%, generally not meeting the Smithfield Agreement EPS of 75% TN removal (Figure 7). The system did not achieve complete nitrification and denitrification, so although ammonium was removed from the waste, the nitrite and/or nitrate concentrations in the N tank effluent were often high.

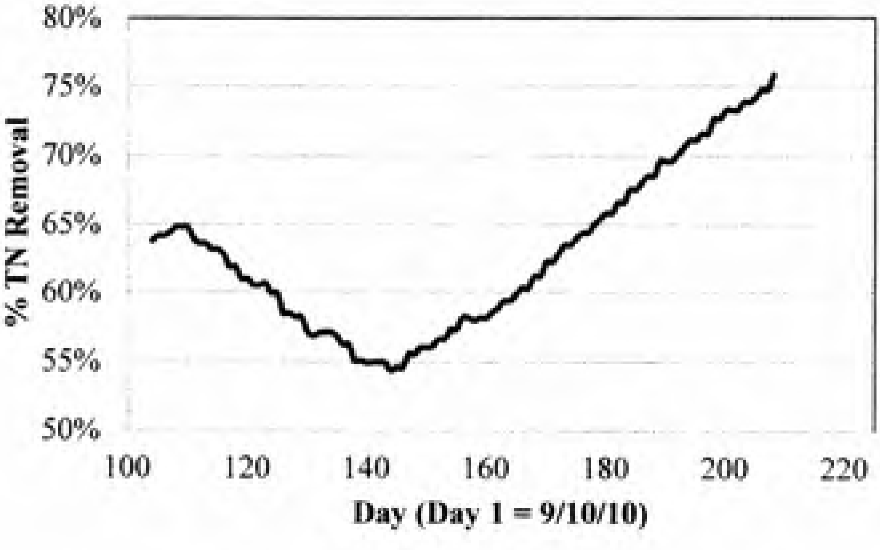

Figure 7 - Percent TN removal (30-day running average) of the pilot scale nitrification/denitrification system.

Additionally, the TN (and assumed ammonium) concentration in the lagoon prior to the installation of the covers was approximately 800 mg/L. Comparing the liquid applied to spray fields before and after the combined system is implemented results in an ammonium reduction of 78% to 95% (average 85%) and a TN reduction of -50% to16%. Because the TN concentration increases dramatically with the installation of the lagoon covers, the TN concentrations in the liquid waste after the combined methane capture and nitrogen removal system can actually be higher than the TN concentration in the lagoon before project activity. This only accounts for nitrogen in the liquid effluent – the combined treatment system prevents the volatilization of ammonia in the lagoon, accounting for the difference in lagoon TN concentrations. Although the pilot scale system did not meet the TN removal EPS used to judge the Smithfield Agreement technologies, TN emissions from swine farms are not currently regulated by the State. At full scale flow rates, this system would meet current state EST regulations regarding ammonia emissions.

The pilot-scale system required the addition of more alkalinity than expected to maintain a suitable pH in the N tank. The total alkalinity available in the lagoon effluent and the alkalinity that can be expected to be produced during denitrification should provide the buffering needed for nitrification, 7.14 g as $CaCO_3$ per g NH_4+-N. However, using the mean data in Table 2, only 5.22 g as $CaCO_3$ per g NH_4^+-N of the alkalinity demand comes from the alkalinity already present in the lagoon effluent. Therefore, for nitrification to be fully buffered, 1.92 g as $CaCO_3$ per g NH_4^+-N must come from denitrification. Assuming complete nitrification and complete denitrification an additional 3.75 g alkalinity as $CaCO_3$ per g NH_4^+-N would be available from denitrification. The additional alkalinity required for nitrification can be provided with as little as 50% denitrification. The system generally saw denitrification rates greater than

50% but 120 lbs. of powdered sodium carbonate were added during reactor operation (3.6 kg/1000 L waste treated). It is uncertain whether this quantity of additional alkalinity was essential or if demand will be reduced in a more consistent full-scale system.

5.0 Full-Scale Design and Expected Performance

5.1 Anaerobic Digester

To prevent the continual accumulation of nitrogen and liquid in the lagoon, the nitrogen loading rate of the nitrogen removal system must be at least as high as the mass of nitrogen and the volume of liquid produced daily by the pigs. To determine the farm's average daily nitrogen production, the farm's annual liquid production was combined with the mean lagoon NH_4^+-N concentration to estimate the daily N loading rate.

The annual liquid production is assumed to be equivalent to the volume of liquid sprayed annually (Table 5).

Table 5 - Volume of lagoon liquid sprayed annually at Butler Farm *(37, 49)*.

Year	Volume Sprayed (L)
2009	3,338,779
2010	4,541,934
2010-2011 spray season	5,818,060
Annual Average	4,566,258

Only records from the years since the lagoon covers were installed were used to determine the annual volume sprayed. The farm's spraying patterns have changed due to the cover. Without rainwater entering the lagoon, less liquid needs to be sprayed and the farmers now intentionally leave some liquid in the lagoon for methane production. To produce a more conservative design (given the limited data), the largest known annual spray volume was chosen to estimate annual liquid production, $Q_{in,y}$. For full-scale design, I therefore assumed that Butler Farms produces 5,818,000 L of liquid each year. This volume includes feces, urine, spilled drinking water, fresh water from cooling sprinklers, and fresh water used to wash the barns. As determined above, the average

NH_4^+-N concentration $\left(C_{NH_4^+-N,L}\right)$ in the lagoon was 2,340 mg NH_4^+-N/L. For full-scale design, I assumed that lagoon effluent has a constant ammonium concentration of 2,340 mg NH_4^+-N/L. The daily mass loading rate for ammonium-N was calculated as follows:

$$Q_{in,y} \times C_{NH_4^+-N,L} = M_{NH_4^+-N,in,y}$$

$$M_{NH_4^+-N,in,y} \div 365\frac{days}{year} = M_{NH_4^+-N,in,d}$$

$$5{,}818{,}100\frac{L}{year} \times 2{,}340\ \frac{mg\ NH_4^+ - N}{L} \approx 13{,}614\frac{kg\ NH_4^+ - N}{year} \approx 37.3\frac{kg\ NH_4^+ - N}{day}$$

Where:

$Q_{in,y}$ = Liquid production from barns in year y (L/year)

$C_{NH_4^+-N,L}$ = Concentration of NH_4^+-N in the lagoon (mg/L)

$M_{NH_4^+-N,in,y}$ = Mass of NH_4^+-N entering the lagoon in year y (mg)

$M_{NH_4^+-N,in,d}$ = Mass of NH_4^+-N entering the lagoon on day d (mg)

The flow rate into the nitrification/denitrification tank from the lagoon must be large enough that 37.3 kg NH_4^+-N enter the tank each day $\left(M_{NH_4^+-N,in,d}\right)$. The corresponding flow rate would be 15,940 L of lagoon liquid per day $\left(Q_{LE,d}\right)$.

The full scale anaerobic digester at Butler Farms has already been constructed, through the covering of the pre-existing anaerobic lagoons. The lagoons are lined earthen containment structures with rectangular bases and sides with a 3:1 slope. Lagoon 1 has a maximum volume of 6.5 million gallons and a surface area of 96,100 ft^2. Lagoon 2 has a maximum volume of 4.5 million gallons and a surface area of 78,120 ft^2 *(37)*. For simplicity, the lagoons are treated as one anaerobic digester with a maximum volume of 11 million gallon. Uncovered anaerobic lagoons are operated at volumes below the maximum volume because farmers attempt to maintain as little volume as possible in the lagoon. The volume of uncovered lagoons is subject to the uncertainty of weather, which can lead to rain accumulation in the lagoons and can prevent land application when the spray field is wet. Though the liquid volume of a covered digester is not influenced by the weather, the digester will be operated at one-half the maximum volume, 5.5 million gallons, to allow for emergency storage capacity and because a larger volume is not necessary to reach the recommended HRT for anaerobic digestion.

For anaerobic lagoons at hog farms, the NRCS Interim Practice Standards 360 requires a minimum HRT of 44 days and a maximum volatile solids loading rate of 10 lbs. VS/1,000 cubic feet *(50)*. An HRT of at least 65 days is recommended to buffer against biomass accumulation, which effectively decreases the volume and thus the HRT of the lagoon *(51)*. Given a lagoon volume of 5.5 million gallons (approximately 20.8 million L) and a flow rate of 15, 940 L/day, the lagoon HRT is an ample 1,306 days. Excessive lagoon volume can be reduced by retrofitting an existing lagoon into nitrification, denitrification and/or storage tanks as discussed in Section 6.2.7.

5.2 Nitrification and Denitrification Tanks

The full scale nitrogen removal system was designed using the same total HRT, 41.3 days, as was operated in the pilot scale system during Period 2. Using the design total HRT (HRT_T) of 41.3 days, the total design volume (V_T) for the nitrification/denitrification system can be calculated.

$$Q_{LE,d} \times HRT_T = V_T$$

$$15{,}940\frac{L}{d} \times 41.3\ days \approx 658{,}400\ L$$

The volume ratio between the N and D tanks will be proportional to the volume ratios in Period 2: the N tank will be four times the size of the D tank. Therefore, the N tank will have a design volume (V_N) of 526,700 L and an HRT (HRT_N) of 33.1 days. The D tank will have a design volume (V_D) of 131,700 L and an HRT (HRT_D) of 8.3 days. Both tanks will be mixed so the solids retention time (SRT) can be assumed equal to the HRT. Like the pilot-scale system, the full-scale system will have an internal recycle ratio of 2.8. Liquid will be pumped from the D tank to the N tank at a rate of 60,572 L/day, and liquid will be pumped from the N tank to the D tank at a rate of 44,632 L/day. Waste will exit the nitrification/denitrification system from the N tank at the same rate as it enters the D tank, 15,940 L/day ($Q_{LE,d} = Q_{N,d}$). The three schemes mentioned in Section 5.0 differ in their treatment of the liquid as it leaves the N tank, as discussed below.

5.3 SCHEME A

In Scheme A, nitrified effluent from the N tank would be used for refilling the pits below the barns and sprayed on the spray fields (Figure 8).

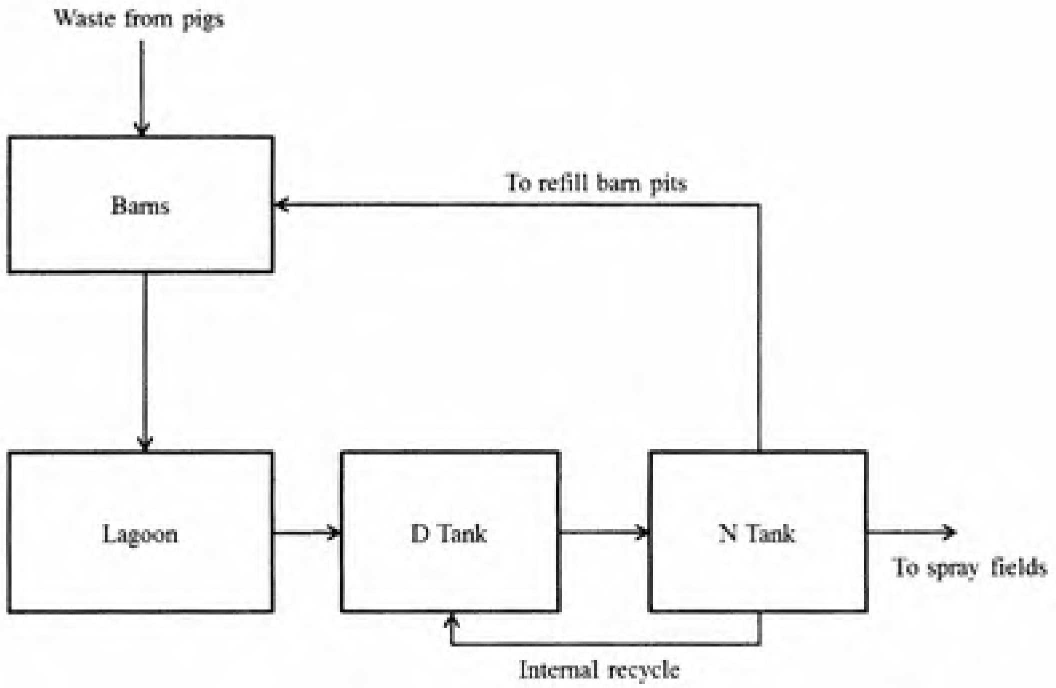

Figure 8 - Scheme A. Effluent from the N tank is used to refill barn pits and is sprayed on the spray fields.

As stated above, the full-scale N tank will have a volume of approximately 658,400 L. Each day the waste collection pits in one or two barns are refilled, requiring 151,400 L or 302,800 L of liquid (each pit is 40,000 gallons or approximately 151,400 L). Ideally, the N tank effluent flow rate will equal 15,940 L/day – the liquid flow rate into the system. In Scheme A, 40-85% of the N tank volume would be removed to refill barn pits each day. The only way to accommodate the volume required for barn flushing is to have a much larger N tank, with a similarly large HRT.

Scheme A also requires additional liquid from the N tank to be used for land application, at an average daily rate equal to the volume entering the system from the N tank each day. Due to North Carolina's spray regulations and the limitations of spraying equipment, some volume equalization in the N tank (*i.e.*, the capability to store effluent) would be necessary. Growers in North Carolina are required to have an individualized waste management plan. The plan at Butler Farms (which is similar to those followed by most growers) allows spraying of waste between April 15 and August 30. In addition, farmers can spray up to 50 lb N/acre on winter cover crops in February and March and another 50 lb N/acre on the winter crops between October 15 and October 31. As is further explained in section 5.6, nitrogen concentrations in the sprayed liquid dictates how much liquid a farmer can spray on a field. Farmers are also limited to when they can spray by the weather - waste cannot be sprayed when the ground is moist or when rain is in the forecast for the next 48 hours *(37)*.

The pumps and hoses used for spraying at Butler Farm and other North Carolina hog farms are large and imprecise. Only large volumes of waste can be sprayed at a time *(37)*. In 2010, waste was applied to the fields on 31 days with an average application of 171,100 L/application day *(49)*. The majority of these spray events took place in groups with three to five spray days per week. Overall, scheme A is infeasible given the current design parameters.

5.4 Scheme B

In Scheme B, liquid from the N tank is returned to the lagoon at the same rate at which liquid enters the nitrification/denitrification system, 15,900 L/day. Liquid from the lagoon is used to refill barn waste collection pits and is applied to the spray fields (Figure 9).

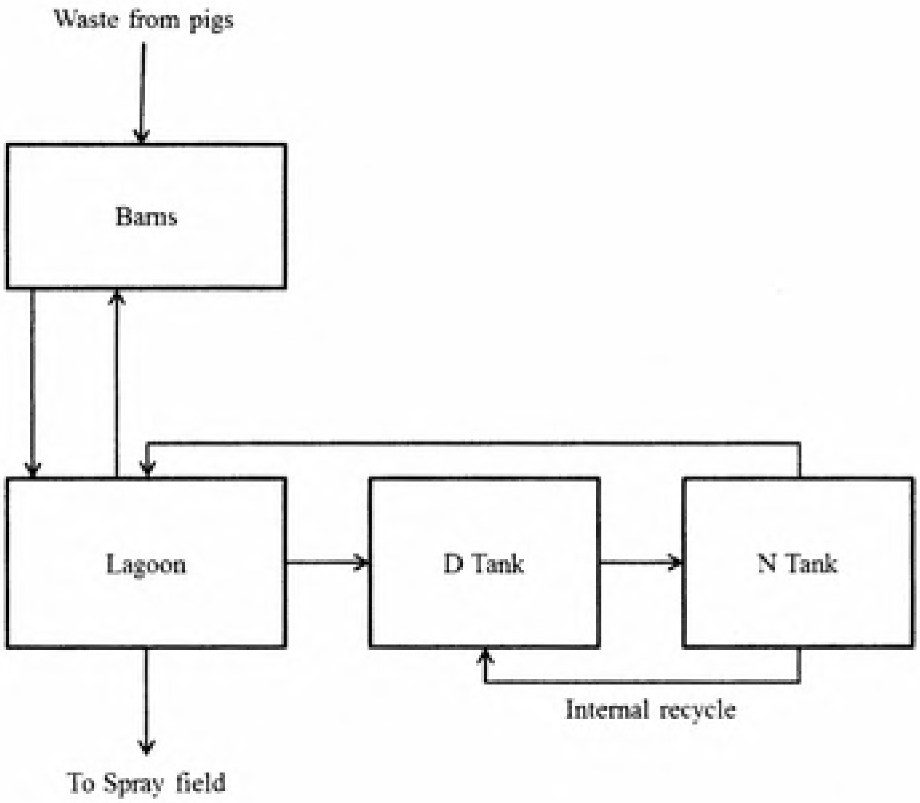

Figure 9 – Full-scale design Scheme B. Effluent from the N tank is returned to the lagoon and liquid from the lagoon is used to refill barn waste collection pits and for land application.

Appendix C includes a model of the inorganic nitrogen species concentrations in the lagoon under Scheme B. Because ammonium is removed in the nitrification/denitrification system and then returned to the lagoon, the lagoon's ammonium concentration will decrease over time, though not to the levels obtained in the N tank effluent. A higher ammonium concentration in the liquid applied to the spray fields results in fewer environmental benefits for the system by decreasing the overall reduction of ammonium and total nitrogen emissions.

5.5 Scheme C

In Scheme C (Figure 10, Appendix D), effluent from the N tank enters a storage tank and is then used for land application. This scheme allows the most treated waste to be used for land application, maximizing the environmental benefits. As with current practices, liquid from the lagoon is used for refilling waste collection pits in the barns.

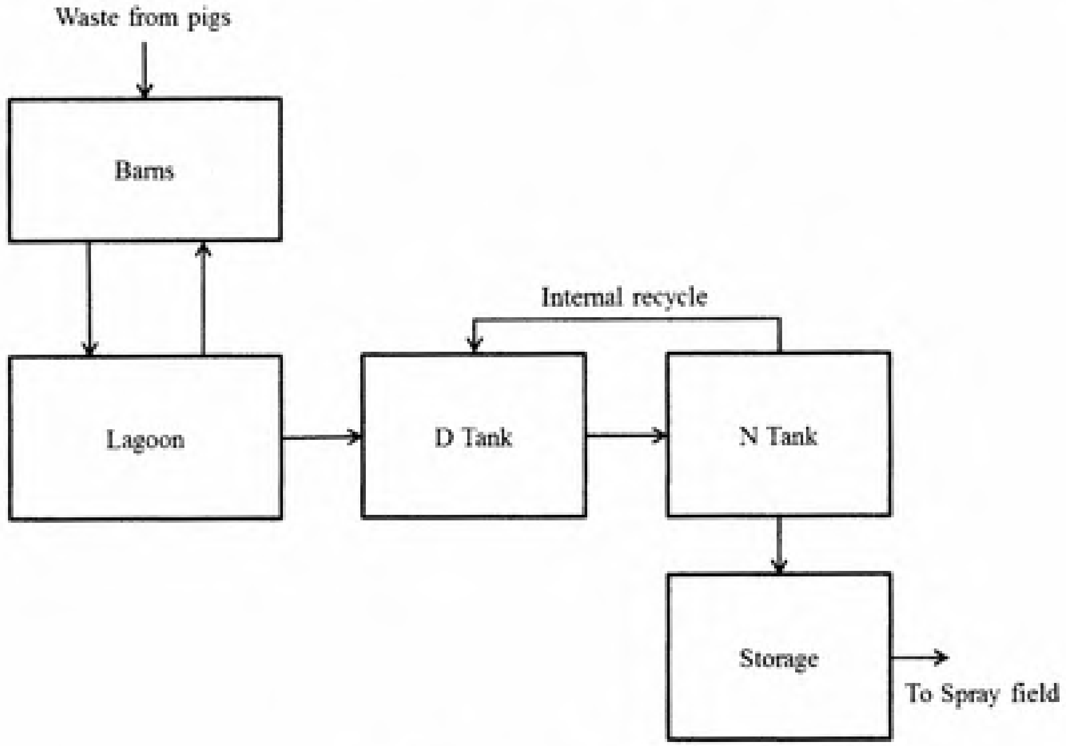

Figure 10 – Full-scale design Scheme C.

As mentioned above, land application of waste occurs sporadically during designated months of the year. The storage tank must be large enough to ensure that enough liquid is available in the storage tank when spraying is permitted. The storage tank can be designed as an equalization tank. Spray records for the 2010-2011 growing season were obtained for Butler Farms and cumulative monthly discharges were compared to the cumulative inflow (Figure 11) *(49)*.

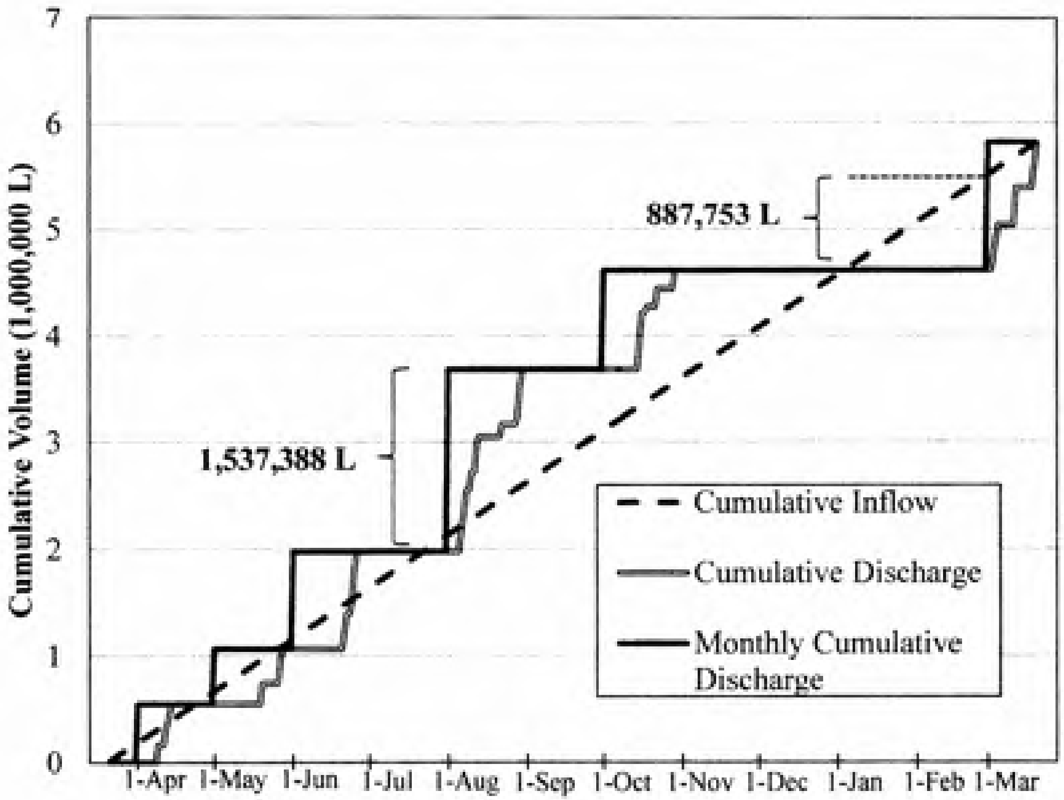

Figure 11 - Cumulative inflow and discharge (land application) for the 2010-2011 growing season.

The storage tank must have a volume equal to the sum of the maximum surplus (1.54×10^6 L) and the maximum deficit (0.89×10^6 L) between the cumulative inflow and the cumulative discharge *(52)*. Monthly cumulative discharge values were used to account for annual variation in spraying patterns. To further account for annual variation, this sum, 2.43×10^6 L, will be increased by 20% to give a design volume of approximately 2.91×10^6 L (790,000 gal).

This scheme uses the most treated waste for land application, maximizing potential environmental benefits. The influent waste and operating parameters remain consistent with the pilot-scale system so comparable ammonia and total nitrogen reductions can be expected. At full scale the lagoon should be heated to maintain a more consistent COD concentration in the lagoon. With less variability, the system should have enough or nearly enough biodegradable COD and alkalinity for complete nitrification and denitrification. Scheme C is both technically feasible and optimizes waste treatment goals and thus is used for further design and cost-benefit analysis.

6.0 Cost-Benefit Analysis

6.1 Assumptions and Limitations

The following analysis attempts to quantify the costs and benefits associated with the adoption of the investigated integrated energy generation and nitrogen removal system. A swine farm with traditional open lagoon and land application practices serves as the baseline for comparison. All costs reflect retrofitting the system to an existing farm with uncovered anaerobic lagoon(s). The cost of lagoons, barns, and all pumps and plumbing required to transport waste to and from the barns is not included in the cost estimate below. Also not included is spraying equipment, lagoon sludge removal and any other costs associated with a typical uncovered anaerobic lagoon system.

Costs and benefits presented reflect an 8,000-head feeder to finish farm in North Carolina with a pull-plug pit flush system. COD and nitrogen loads, and thus expected system performance, will vary with type of farm, size of farm, location of farm, and type of barn flush system used. Costs and benefits are reported as 10-year annual costs/benefits (annual costs over a 10-year period) per 1000 pounds of steady-state live weight ($/1000 lbs. SSLW) to provide values which can more easily be used for other farms. This reporting unit was adopted from the economic reports associated with the Smithfield Agreement technologies *(20)*. Estimates use a 10-year economic life and an 8% interest rate as used by the economic subcommittee responsible for Smithfield Agreement technologies *(53)*. The assumed SSLW for a feeder to finish farm is 135 lbs. per pig, meaning that this is the average weight of a pig during its time at the farm (approximately 20 weeks) *(37, 54)*. At 8,000-head, Butler Farms has a total SSLW of 1,080,000 lbs.

When possible, cost and benefit information specific to Butler Farms was used. This includes lagoon cover costs, generator set costs, farm power consumption, unit power costs, unit power benefits, and grower preferences. Some variation can be expected with location (transportation costs, power costs), size of farm (unit cost of excavation and cover decreases with size), and potentially waste characteristics (alkalinity and biodegradable COD available, methane production).

Where Butler Farms-specific pricing information was not available, pricing assumptions were adopted from the assumptions used by Kelly Zering in his costs and returns analysis of the technologies investigated as part of the Smithfield Agreement *(51, 55)*. All cost and return values presented are in 2011 dollars. Costs and returns (including pricing assumptions from the Smithfield Agreement technologies reports) were converted to 2011 dollars using the consumer price index (CPI-U) (see Appendix E). An overhead cost of 20% was assumed on all construction costs unless explicitly included in charges and price quotes. This overhead cost accounts for engineering services, mobilization, contractors' profits, taxes, insurance, and contingencies. The overhead cost assumption differs from the assumed 43.1% of construction costs used in the Smithfield Agreement economic feasibility reports *(51)*. This modification is a result of the criticism the group received for that assumption *(56, 57)*.

6.2 Costs

6.2.1 Lagoon Cover and Methane Capture System

The lagoon cover and methane capture system costs are defined as all initial material, installation, and overhead costs associated with the collection of biogas and its delivery to the generator. The cost of a flare is included in this system. A flare is necessary for combusting GHGs that are not consumed by the generator or for combusting biogas that is not entering a generator. At Butler Farms, Lagoon 1 has a surface area of 96,100 ft^2 and Lagoon 2 has a surface area of 78,120 ft^2 for a combined cover area of 174,220 ft^2. The lagoon covers and methane capture system at Butler Farms were installed by Environmental Fabrics, Inc. in 2008 for a turn-key price of $360,000 *(37, 38)*. This price includes the covers, all piping necessary for biogas collection, flare, gas blower, equipment to remove rain from the cover, gas flow meter, and all engineering, installation, and overhead charges. For other farms, the cost of the cover and methane capture system will vary with lagoon surface area and distance to flare/energy generation station.

Zering assumed covers from Environmental Fabrics, Inc. to cost \$1.87/ft^2 for installations involving 20,000 ft^2 or less and \$1.05/ft^2 for installations 140,000 ft^2 or greater. For projects between 20,000 ft^2 and 140,000 ft^2 unit costs vary linearly between these two known unit costs. These prices reflect the cost of materials, equipment to clear rain from the cover, and excess material necessary for anchoring *(51)*. Based on these assumptions, the indicated materials for the Butler Farm lagoon covers cost $180,831 and the remaining $179,169 of the $360,000 cost would be attributed to gas collection equipment, gas monitoring equipment, the flare, and installation, engineering, and overhead charges.

6.2.2 Energy Production System

The energy production system is defined as all initial materials, installation, and overhead costs associated with generation of electricity and heat and their consumption by the farm and/or delivery to the grid. A combined heat and power generator-engine set was selected (as opposed to a system which did not utilize the heat generated during combustion) so that the denitrification reactor, nitrification reactor, and lagoons could be heated to temperatures that are more favorable for their respective processes. Methane combustion has the potential to produce 891 kJ/mole CH_4:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l) + 891 \text{ kJ/mole}$$

The proposed generator set includes a 100 kW Man generator and six-cylinder in-line engine set *(37)*. At load rates of 100% and 75% the generator set has mechanical efficiencies of 38.6% and 37.8%, thermal efficiencies of 53.7% and 51.8%, and total efficiencies of 92.3% and 89.7%, respectively *(58)*. The fabrication, transportation, and installation of the generator set, the installation of switchgear, the installation of a telemetry system, and the structure to house these items are reflected in the first item cost in Table 6. All costs reported in Table 6 include fabrication, transportation, and installation of their respective components when applicable.

Table 6 - Costs of Energy Production System *(37, 51)*

Component	**Cost**
Generator set, Switchgear, and Telemetry in modular container	$181,500
Standby Radiator	$7,700
Hydrogen Sulfide Scrubber	$38,500
Heat Recovery	$7,150
Biogas Filter	$1,430
Biogas Dryer	$7,700
Electrical Installation	$33,000
Gas Piping Installation	$5,500
Lagoon, N Tank, D Tank Heating/Pump and Piping	$75,900
Metering Package	$7,700
Site Preparation	$5,500
Engineering	$33,000
Total Cost of Energy Production System	**$404,580**

After leaving the lagoon, the gas will first pass through a filter to remove particulate matter and a hydrogen sulfide (H_2S) scrubber. The hydrogen sulfide scrubber will reduce the amount of hydrogen sulfide in the biogas before it enters and corrodes the generator set, which would reduce its life. The scrubber will also prevent the odorous hydrogen sulfide from entering the atmosphere, where it can also create hazardous sulfur dioxide (SO_2) *(59)*. The USEPA heavily regulates the emissions of sulfur dioxide, which can cause respiratory illness *(60)*. Hydrogen sulfide is emitted from uncovered anaerobic lagoons at rates of approximately 0.57 $\mu g\ m^{-2}\ s^{-1}$. For Butler Farms this equates to 291 kg per year. After the scrubber, the biogas will pass through a dryer to remove moisture and prepare the gas for combustion.

The farm will operate under a net-metering contract with the local utility company, meaning that all electricity produced by the generator set will be used first to meet the demands of the farm with only residual power sold to the grid. Currently in North Carolina, most farms are charged more per kWh consumed than they would receive from the utility company for producing one kWh. If revenue per kWh were to increase beyond the average charge per kWh, the farm should sell all electricity generated. The electrical installation cost in Table 6 reflects the cost of installing and wiring all electrical components associated with the connection to the grid and the actual connection to the grid *(51)*.

A heat exchange system will use water to cool the engine and transport the heated water to the denitrification tank, the nitrification tank, and the lagoon. Capturing and utilizing the waste heat of electricity generation increases the effective efficiency of the system and will provide necessary heat to the reactors and lagoon. As was observed during pilot-scale operation, the lagoon temperature became prohibitively low (with respect to methane production) during winter months. Tom Butler reports having difficulty lighting his flare during much of November 2010 and March 2011 and being completely unable to do so December 2010 through February 2011 *(37)*. At full-scale, the nitrification and denitrification tanks will be housed in an earthen containment structure similar to a lagoon (albeit much smaller) where low temperatures will reduce nitrogen removal by slowing growth of nitrifying and denitrifying bacteria *(22, 61, 62)*. The nitrogen removal rates reported above reflect the reactor temperatures during pilot-scale operation.

The site preparation cost includes grading, erosion and sediment control, and a concrete slab to serve as the foundation for the generator set containment structure. Engineering costs reflect costs of project management, design, permitting, and construction oversight.

6.2.3 Nitrification-Denitrification System

The cost of the nitrification-denitrification system is defined as all construction, initial materials, installation, and overhead costs associated with treating the liquid after it leaves the lagoon and before it reaches the storage tank. As determined above, the liquid in and out of the system will equal 15,940 L/day (563 ft^3/day). This design flow rate corresponds to a N/D system volume of 658,400 L (23,250 ft^3), an N tank volume of 526,700 L (18,600 ft^3) and a D tank volume of 131,700 L (4,650 ft^3). All further design calculations will use imperial units as those are used by contractors for pricing and in the Smithfield Agreement reports.

Construction costs of the N and D tanks were compared for three construction alternatives – an earthen containment structure, a concrete containment structure, and steel tanks (Table 7). See Appendices F-J for design and cost calculations. An earthen containment structure was found to have the lowest construction cost.

Table 7 - Cost estimate for four N/D tank construction alternatives (2011 dollars).

System		Cost
Earthen containment structure	Excavation	$4,815
	Plastic Liner	$9,995
	Baffle	$781
	Overhead	$2,962
	Total	**$18,554**
Concrete containment structure	Concrete basin	$25,441
	Baffle	$580
	Overhead	$5,088
	Total	**$31,109**
Steel tank (one divided tank)	Tank	$52,309
	Baffle	$907
	Overhead	$10,462
	Total	**$63,678**
Steel tanks (separate N and D tanks)	N tank	$45,923
	D tank	$22,559
	Overhead	$13,696
	Total	**$82,178**

One trapezoidal earthen containment structure with a dividing curtain will be used for both the N and D tanks. The earthen containment structure will have the same design as an earthen lagoon (see design calculations in Appendix F). The containment structure will have a base area 18 ft. x 18 ft., a top area of 96 ft. x 96 ft., 3:1 sloped sides, and a depth of 13 feet (including 1 foot of structural freeboard and 2 feet of emergency storage). The designed liquid depth is 10 feet with a liquid surface area of 78 ft. x 78 ft.

Excavation costs assume that only 70% of the volume will be excavated, as existing terrain and excavated soil will be utilized. Assumed excavation costs are \$3.80/yd^3 *(51)*.

The containment structure will be lined with a plastic liner to prevent the wastewater from leaking from the reactors. The price of the liner assumes that the surface area required is the surface area inside the containment structure plus 8% of the area to be used for anchoring the liner. The containment structure will require a 25,626 ft^2 liner at \$0.37/ft^2. See Appendix G for detailed calculations.

A pH control system will be installed in the N tank to prevent the pH in the N tank from falling below a level amenable for biological nitrification. The system will automatically pump a concentrated sodium carbonate solution into the N tank when the pH reaches a set target (approximately 6.8). pH control systems can vary in complexity and on a large scale are built using components from multiple manufacturers. An automated system would include a concentrate mix tank, a mixer and controls for the mix tank, a pH monitoring system for the N tank, a pump to deliver the sodium carbonate concentrate to the N tank, a process control system to link the pH monitoring system with the sodium carbonate delivery system, and all related piping and electrical connections. The Super Soils technology examined as part of the Smithfield Agreement included a pH control system, but other technologies explored did not include pH control in their reported costs. The same concentrate mixing tank (\$1,183), concentrate mixer (\$1,124), and pipe installation and fittings (\$2,343) costs as the Super Solids Second Generation system will be assumed as these were the only costs reported relevant to the pH control system *(55)*. The costs of a pH monitoring system (\$2,550) *(63)*, diaphragm injection pump (\$375) *(64)* and 20% overhead charges (\$1,515) were added to give a total cost of

$9,090. The annual cost of sodium carbonate and associated electricity costs are considered operations and maintenance costs.

Oxygen will be delivered to the N tank using high-density grid-type fine bubble diffusers. Aeration grids will be installed on the base of the N tank and on the lower sections of the sloped walls. At full scale, the system will be aerated using air instead of pure oxygen due to the high cost of oxygen gas. Stoichiometrically, the system will require 4.57 g O_2/g NH_4^+-N, or 171 kg of O_2/day, for complete nitrification. The partial nitrification achieved in the pilot scale system required an average of 3.76 g O2/g NH_4^+-N entering the system (140 kg O_2/day at full scale) (see Appendix K). EW2 Environmental, Inc. quoted an Environmental Dynamics International system that includes two 10-HP rotary lobe blowers for $17,000 *(103)*. This price includes installation but is subject to an additional 20% overhead cost, $3,400, for a total cost of $20,400. The cost of associated electricity consumption will be addressed in the operation and maintenance section.

The system will use gravity to carry liquid from the lagoon to the D tank and from the N tank to the storage tank. A pump will be required to transport liquid from the D tank to the N tank and recycle liquid from the N tank to the D tank. Continuous duty pumps are required that can accommodate the design flows. Depco Pump Company quoted a cost of $1,008 each for 1-HP Oberdorfer pumps *(104)*. Piping costs are estimated to be $2,000, based on piping and plumbing costs reported for the Super Soils and Barham Farm technologies. The D tank will require a mixer ($1,400) to keep the reactor completely mixed *(55)*.

6.2.4 Storage Tank

As determined in 4.4.4, a 2.91×10^6 L (102,800 ft^3) storage tank is required. Using the same methods as in Appendices F-J, the costs of an earthen containment structure, concrete containment structure, and steel tank was calculated (Table 8).

Table 8 - Cost estimate for full scale storage tank alternatives.

System		Cost
Earthen containment structure	Excavation	$15,535
	Plastic Liner	$15,310
	Overhead	$6,169
	Total	**$37,014**
Concrete containment structure	Concrete basin	$63,176
	Overhead	$12,635
	Total	**$75,811**
Steel tank (1)	Tank	$158,754
	Overhead	$31,751
	Total	**$190,505**
Steel tank (2)	Tank	$164,262
	Overhead	$32,852
	Total	**$197,114**

As with the N/D system, an earthen containment structure is the lowest-cost alternative. Because an earthen containment structure will be used for both the reactors and the storage basin, a lower unit excavation cost, corresponding to overall excavation, was used.

The earthen containment structure will have a base area 70 ft. x 70 ft., a top area of 148 ft. x 148 ft., 3:1 sloped sides, and a depth of 13 feet (including 1 foot of structural freeboard and 2 feet of emergency storage). The designed liquid depth is 10 feet with a liquid surface area of 130 ft x 130 ft. Excavation costs assume that only 70% of the volume will be excavated as existing terrain and excavated soil will be utilized. Assumed excavation costs are \$3.80/yd^3.

The containment structure will be lined with a plastic liner to prevent the nitrified effluent from leaking from the storage basin. The price of the liner assumes that the surface area required is the surface area inside the containment structure plus 8% of the area to be used for anchoring the liner. The containment structure will require a 24,650 ft^2 liner at \$0.37/ft^2. See Appendix G for detailed calculations.

6.2.5 Operation and Maintenance

Annual costs associated with the full scale system include electricity costs, the cost of sodium carbonate and maintenance costs. The power demands and electricity costs listed in Table 9 reflect power estimates made by Zering and by component manufacturers *(55, 63, 64)*. The cost of the biogas blower was assumed negligible *(51)*. Electricity costs were listed for the actual price at Butler Farms. \$0.096/kWh *(37)*, and for a high and low electricity price to show the sensitivity of annual energy costs. The cost using a unit price of \$0.096/kWh will be used for further cost-benefit analysis.

Table 9 - Daily power demands and energy costs of a full scale methane capture and nitrogen reduction system at Butler Farms.

Unit/Process	Daily Power Requirements (kWh/day)	Annual Cost		
		Low Cost (\$0.08/kWh)	Base-Case Cost (\$0.096/kWh)	High Cost (\$0.12/kWh)
D Tank to N Tank Pump	19.67	\$574	\$689	\$862
N Tank to D Tank Pump	19.67	\$574	\$689	\$862
pH Control	7.2	\$210	\$252	\$315
N Tank Aeration/Blowers	220.8	\$6,447	\$7,737	\$9,671
D Tank Mixer	83.95	\$2,451	\$2,942	\$3,677
Total	**351.29**	**\$10,258**	**\$12,309**	**\$15,387**

During pilot scale operation, 120 lbs. of powdered sodium carbonate were added to the nitrification tank, or approximately 3.6 kg/1000 L. If an equivalent demand from the full scale system is required, the N tank will require approximately 20,700 kg/year (45,600 lbs./year). Available for $0.44/lb., annual sodium carbonate costs are approximately $20,000/year *(65)*.

Maintenance cost assumptions are adopted from the assumptions used in the Smithfield Agreement economic feasibility reports. An annual maintenance cost of 2% and 5% was assigned to all non-moving and moving parts, respectively (Table 10).

Table 10 - Estimated annual maintenance costs for a full scale methane capture and nitrogen removal system on Butler Farms.

Item	Annual Maintenance Cost
Lagoon Cover	$3,617
Gas Collection Equipment	$3,583
Generator Engine Set	$9,075
Standby Radiator	$385
Hydrogen Sulfide Scrubber	$770
Biogas Filter	$29
Biogas Dryer	$154
Heating Pump/Piping	$1,518
N/D Tank	$215
Storage Tank	$306
pH Control	$379
Aeration + Blowers(66)	$850
N/D Pumps	$101
Piping	$40
D Tank Mixer	$70
Total	**$21,092**

6.2.6 Cost Summary

The information presented in Sections 6.2.1 through 6.2.5 was summarized to arrive at an overall system cost. At full scale, the investigated methane capture and nitrogen removal system will cost $168/1,000 lbs. SSLW (Table 11). The cost is comparable to the technologies developed for the Smithfield Agreement (Table 1). The cost includes $862,289 for initial construction and $53,026 annually for operations and maintenance. Costs reported reflect a 10-year economic life and an 8% interest rate.

Table 11 - Cost of full scale combined methane capture and nitrogen removal system at Butler Farms. Reported annualized costs assume an 8% interest rate.

System	Cost	Annual Cost (10-Year)	10-Year Annualized Cost ($/1,000 lbs. SSLW)	% 10-Year Annualized Cost
Capital Costs				70.8%
Lagoon Cover and Methane Capture	$360,000	$53,651	$49.68	29.6%
Energy Production	$404,580	$60,294	$55.83	33.2%
Nitrification/Denitrification Tank	$18,550	$2,764	$2.56	1.5%
Storage Tank	$37,041	$5,520	$5.11	3.0%
pH Control	$16,447	$2,451	$2.27	1.4%
Aeration + Blowers	$20,372	$3,036	$2.81	1.7%
Pumps	$2,419	$361	$0.33	0.2%
Denitrification Tank Mixer	$1,200	$179	$0.17	0.1%
Piping and Plumbing	$1,680	$250	$0.23	0.1%
Operation and Maintenance Costs				29.2%
Electricity Consumption		$12,309	$11.40	6.8%
Sodium Carbonate		$20,000	$18.52	11.0%
Maintenance		$21,717	$19.18	11.4%
Total	**$862,289**	**$181,532**	**$168.09**	100.0%

Table 12 displays the sensitivity of the system's cost to economic life and interest rate.

Table 12 - The effect of economic life and interest rate on the annualized cost of a full scale methane capture and nitrogen removal system.

	Annualized Cost ($/1,000 lbs. SSLW)
Low-Cost Projection (15-year economic life, 6% interest rate)	$131.30
Actual Cost Projection (10-year economic life, 8% interest rate)	$168.09
High-Cost Projection (7-year economic life, 10% interest)	$213.10

A significant portion of the estimated system cost, 11 percent, is attributed to the annual consumption of sodium carbonate. The data collected during pilot-scale operation does not provide conclusive information about the necessity for the addition of sodium carbonate. As previously mentioned, none of the candidate ESTs explored through the Smithfield Agreement incorporated a pH control system in their denitrification reactors. If the pH control system were able to be eliminated from a full-scale system, the system cost could be reduced by $20,000/year, or $18.52/1000 lbs. SSLW/year. As discussed in Section 8.0, further investigation of the technology could lead to significant cost savings.

6.2.7 Butler Farms-Specific Retrofitting Alternative

Butler Farms currently uses two lagoons, although design calculations presented above assumed one large lagoon. If Scheme C were used, the smaller of the two lagoons, Lagoon 2, could be converted into the N tank, D tank and storage tank using baffles. Digestion of hog waste requires a lagoon HRT of at least 44 days *(50)*. Assuming Q_{in} = 15,940 L/day, the farm could operate with only Lagoon 1 (maximum capacity 24.6

million L) and a lagoon HRT of 1,543 days. Even if Lagoon 1 were operated at one-quarter of its capacity, the anaerobic digester would have an HRT of 386 days.

Lagoon 2 has a maximum capacity of 20.8 million L. The total volume required for the N tank, D tank and storage tank is 3.6 million L. The extra capacity allows for flexibility with system flow rates and HRTs, and it provides emergency storage capacity. HDPE fabric will be used to separate the Lagoon 2 into the three tanks. These HDPE baffles have a total cost of $5,733 (Appendix I). Additionally, the cost of the lagoon cover can be reduced because only Lagoon 1 will be covered. The reduction in the cost of two covers ($180,831) is proportional to the size of Lagoon 2 relative to the combined sizes of Lagoon 1 and 2. By eliminating the construction of the N tank, D tank, and storage tank, and reducing the lagoon cover cost the initial project cost is reduced to $731,347 with a 10-year annualized cost of $148/1,000 lbs. SSLW (Table 13). The retrofitting solution is expected to save $20/1,000 lbs. SSLW and reduce the system's footprint at Butler Farms.

Table 13 - Cost of Butler Farms retrofitted full scale methane capture and nitrogen removal system. Reported costs assume an 8% interest rate.

System	Cost	Annual Cost (10-Year)	10-Year Annualized Cost ($/1,000 lbs. SSLW)	% 10-Year Annualized Cost
Capital Costs				68.1%
Lagoon Cover and Methane Capture	$278,916	$41,567	$38.49	26.0%
Energy Production	$404,580	$60,294	$55.83	37.7%
Baffles	$5,733	$854	$0.79	0.5%
pH Control	$16,447	$2,451	$2.27	1.5%
Aeration + Blowers	$20,372	$3,036	$2.81	1.9%
Pumps	$2,419	$361	$0.33	0.2%
Denitrification Tank Mixer	$1,200	$179	$0.17	0.1%
Piping and Plumbing	$1,680	$250	$0.23	0.2%
Operation and Maintenance Costs				31.9%
Electricity Consumption		$12,309	$11.40	7.7%
Sodium Carbonate		$20,000	$18.52	12.5%
Maintenance		$19,063	$17.65	11.7%
Total	**$731,347**	**$159,989**	**$148.14**	100.0%

Table 14 displays the sensitivity of the system's cost to economic life and interest rate.

Table 14 - The effect of economic life and interest rate on the annualized cost of a retrofitted full scale methane capture and nitrogen removal system at Butler Farms.

	Annualized Cost ($/1,000 lbs. SSLW)
Low-Cost Projection (15-year economic life, 6% interest rate)	$116.94
Base-Case Cost Projection (10-year economic life, 8% interest rate)	$148.14
High-Cost Projection (7-year economic life, 10% interest)	$186.31

A similar retrofitting scheme could be adopted by other farms with multiple existing lagoons or by dividing a large existing lagoon into the anaerobic digester, N tank, D tank and storage tank. In the latter case, care would have to be taken to preclude mixing of the atmosphere in the anaerobic digester with the aerobic atmosphere of the N tank.

6.3 BENEFITS

6.3.1 ENERGY PRODUCTION

The biogas production and capture at Butler Farms has been monitored by the Environmental Credit Corporation since the installation of the lagoon covers in 2008. Observed biogas production is shown in Figure 12. Currently, biogas production varies seasonally due to fluctuations in the lagoon temperature. At full scale, the excess heat from the generator will be used to maintain a more constant temperature in the lagoon. The digesters produce approximately 4,750,000 ft^3 of biogas per year – significantly less than the 18,992,400 ft^3 of biogas predicted by the EPA's Farmware software *(67)*. Further calculations will assume a constant biogas production rate of 542 ft^3/hour (14,840 L/hour) (Table 15).

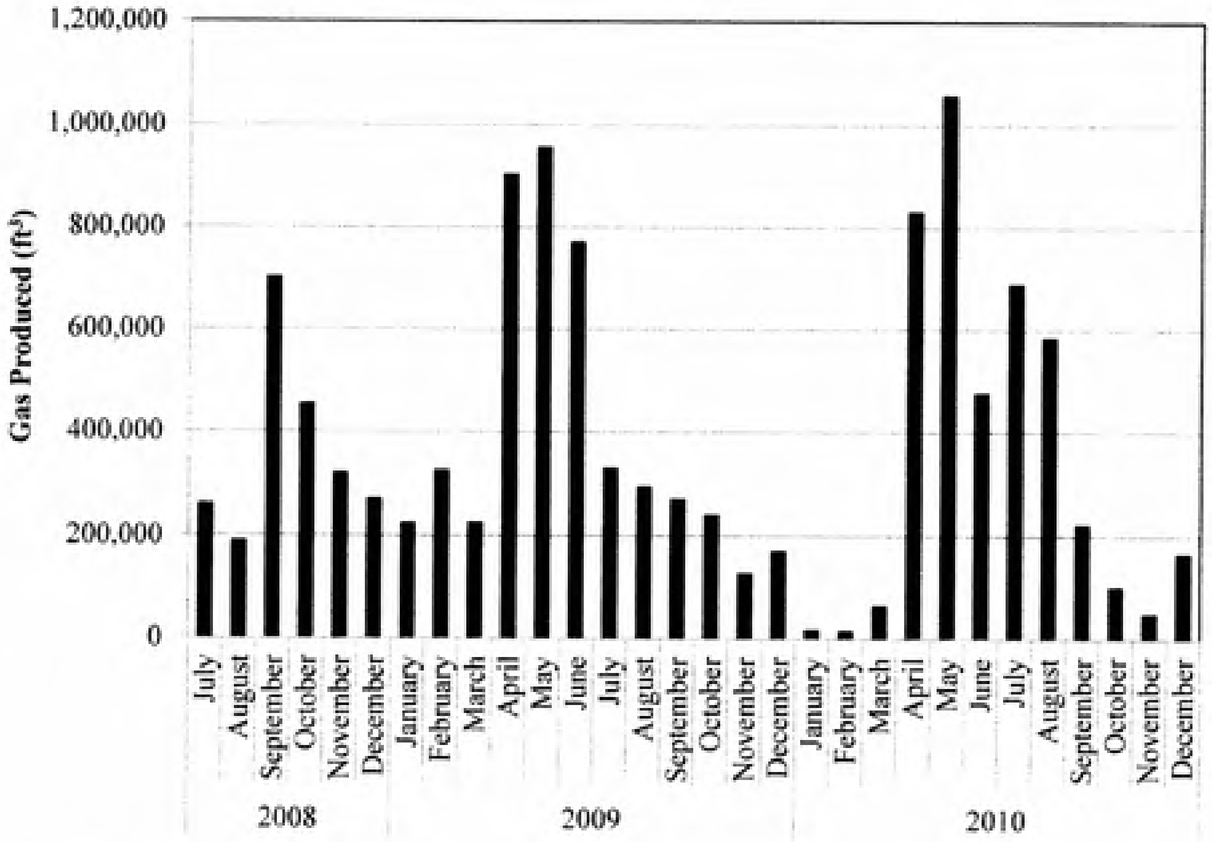

Figure 12 - Full-scale gas production in covered lagoons. Gas measured in standard cubic feet.

Table 15 - Average monthly biogas production July 2008 through December 2010.

Month	Average Monthly Biogas Produced (ft^3)	Hours/Month	Average ft^3 of Biogas/Hour
January	120,998	744	163
February	170,898	672	254
March	144,875	744	195
April	866,811	720	1,204
May	1,007,328	744	1,354
June	623,634	720	866
July	426,749	744	574
August	356,098	744	479
September	398,081	720	553
October	265,154	744	356
November	166,000	720	231
December	203,031	744	273
TOTAL	**4,749,654**	**8,760**	
AVERAGE	**395,805**	**730**	**542**

The biogas at Butler Farms was found to be 56.6% methane (Table 16). Further measurements may reveal a higher or lower methane concentration and thus affect potential energy benefits, as biogas with a higher methane concentration has a higher energy potential during combustion. Note that the gas composition measurements did not include H_2, a known product of anaerobic digestion with significant energy content.

Table 16 - Gas composition at Butler Farms as measured by The Animal and Poultry Waste Management Center, July 2010 *(41)*.

Gas	Composition (%)
Methane	56.6
Oxygen	<1
Nitrogen	20.4
Carbon Dioxide	19
Moisture	1

In his economic analysis of Barham Farm, Zering assumed that a generator will produce 38.2 kWh/1,000 ft^3 of methane *(51)*, while the Farmware software produced by the EPA suggests a production of 71.5 kWh/1,000 ft^3 of methane *(67)*. Assuming a biogas flow rate of 542 ft^3/hr and a methane fraction of 56.6%, the anaerobic digester will produce 307 ft^3 CH_4/hr or 2,689,000 ft^3 CH_4/year. This will result in an energy production of 103,000 kWh/year or 192,000 kWh/year using the Zering or Farmware energy production assumptions, respectively.

Butler Farms currently spends approximately $17,000 per year on electricity to power farm operations, including the methane capture system currently in place. The addition of a nitrogen removal system will more than double energy demand, increasing the annual electricity cost to over $29,000 (Table 17). The energy demand at Butler Farms increases in the summer due to the use of cooling fans and sprinklers in the barns *(37)*.

Table 17 - Current and projected annual electricity consumption and costs at Butler Farms. Assumes an electricity cost of $0.096/kWh and an additional demand of 517.57 kWh/day. Current energy consumption and charges are from 2010 (37).

	Current Consumption		Including Nitrogen Removal	
	kWh	Charge	kWh	Projected Cost
January	9,400	$902	20,290	$1,948
February	9,680	$929	19,516	$1,874
March	10,500	$1,008	21,390	$2,053
April	15,600	$1,498	26,139	$2,509
May	15,600	$1,498	26,490	$2,543
June	18,000	$1,728	28,539	$2,740
July	24,600	$2,362	35,490	$3,407
August	24,900	$2,390	35,790	$3,436
September	26,100	$2,506	36,639	$3,517
October	8,100	$778	18,990	$1,823
November	5,100	$490	15,639	$1,501
December	8,400	$806	19,290	$1,852
SUM	**175,980**	**$16,894**	**304,201**	**$29,203**
AVERAGE	**15,690**	**$1,506**	**25,350**	**$2,434**

The electricity charge per kWh provided by the local power utility, South River Electric Membership Corporation, is $0.096, while the payment for energy production is only $0.048/kWh. As previously stated, the energy production system will include a net-metering connection and contract that will allow the energy produced to be used on site before remaining electricity is sold onto the utility grid. Electrical demand projections indicate that no surplus power will be available and that Butler Farms must continue to purchase additional electricity from the power utility. If the payment for producing electricity ever exceeds the purchase price, power produced should be sold directly to the power utility. Using the Zering and Farmware electricity production assumptions, Butler Farms can save $9,900 to $18,400, respectively (Table 18). The swine farm methane capture pilot program that was introduced by the NC General Assembly in 2007 set a maximum electricity buy-back price of \$0.18/kWh *(18, 68)*. Unfortunately, only swine farms located on a public utility grid are eligible for the program and the buy-back price. This buy-back price could double annual electricity benefits and will be used in the best-case scenario during cost-benefit analysis. The energy production system can meet 80% to 150% of the energy demand created by the nitrogen removal system and 34% to 63% of the total projected farm demands. Further analysis will only consider a power production of 38.2 kWh/1,000 ft^3 as the Farmware software has been found to overestimate biogas production at Butler Farms as well as biogas and power production at Barham Farm *(37, 51)*.

Table 18 - Projected power production, savings and fraction of energy demand met using Zering and Farmware electricity production assumptions.

	Zering, 38.2 kWh/1,000 ft^3	Farmware, 71.5 kWh/1,000 ft^3
Power Production (kWh/year)	102,656	192,144
Annual Savings (\$0.096/kWh)	\$9,855	\$18,446
10-Year Annualized Savings - \$/1,000 lbs. SSLW (\$0.096/kWh)	\$9.12	\$17.08
Annual Savings (\$0.18/kWh)	\$18,478	\$34,586
10-Year Annualized Savings - \$/1,000 lbs. SSLW (\$0.18/kWh)	\$17.11	\$32.02
% of Additional Demand Met	80%	150%
% of Total Demand Met	34%	63%

In addition to direct monetary savings on electricity, energy production from methane will generate renewable energy certifications (RECs) with each REC representing the non-power attributes associated with the production of one MWh of renewable electricity *(69)*. Developed in the late 1990s, these credits can be traded in voluntary markets or sold to governments and corporations that must meet mandated renewable energy goals *(70)*. Twenty-nine states, including North Carolina, currently have renewable energy portfolio standards (REPS), which require the state to obtain a minimum fraction of its power from renewable sources by a given year *(71)*. North Carolina requires that by 2021, public utility companies supply 12.5% of the 2020 power demands from renewable energy sources. Electric Membership Corporations, such as the company that provides power for Butler Farms, are only required to supply 10% of 2017 power demands from renewable energy sources by 2018. All retail electricity suppliers are expected to meet 0.2% of power demand with energy created from swine waste by 2018 *(18)*. Most states, including North Carolina, allow RECs to be used towards REPS goals *(18)*. The North Carolina Renewable Energy Tracking System (NC-RETS) was established to create, verify, and track RECs created in the state and used by the state to meet REPS. Other states and regions have similar tracking and monitoring systems *(72, 73)*.

As with other trading markets, the price of RECs varies, affected by the type of renewable energy and whether the REC is being sold in a voluntary or compliance market. REC prices are expected to shift as more entities are required to comply with non-voluntary renewable energy goals and as more RECs enter the market *(70)*. In the past several years, unbundled biomass RECs have varied between $1/REC and $50/REC, varying with the market in which the RECs were sold and the REC's state of origin *(70, 74, 75)*. Some state REPS specify a portion of claimed renewable energy that must be produced in-state and some require that RECs be bundled *(70)*. The price of biomass RECs is similar to the prices for other renewable energy sources except for solar; solar RECs are often sold for $30/REC to $300/REC *(70, 75)*. Potential revenues from RECs at Butler Farms are shown in Table 19. A REC price of $10 will be assumed for further analysis. Compared to estimated annualized costs (Table 13), RECs at this price would have a negligible impact on net costs for the proposed integrated system.

Table 19 - Projected annual revenue from REC sales at Butler Farms. Assumes an annual power production of 102,656 kWh.

REC Price	Annual Revenue	10-Year Annualized Benefit ($/1,000 lbs. SSLW)
$1/MWh	$103	$0.10
$5/MWh	$513	$0.48
$10/MWh	**$1,027**	**$0.95**
$20/MWh	$2,053	$1.90
$50/MWh	$5,133	$4.75

6.3.2 Greenhouse Gas Credits

Greenhouse gas credits can be claimed for the methane captured and converted to energy. The reduction in greenhouse gas emissions is the difference between the annual baseline emissions (BE_y) and the annual project emissions (PE_y) using the United Nations Framework Convention on Climate Change's Clean Development Mechanism method AMS III D (Appendix M) *(76, 77)*. The baseline emissions are those associated with the operation of a hog farm with uncovered lagoons and which uses land application for waste disposal. The project emissions are those associated with the operation of the project system (fossil fuel for power, transportation, the N/D system) and those that escape the capture system (through leakage, flaring, and storage). Gas emissions from the full scale N and D tanks (CO_2, CH_4, N_2O, NH_3) are calculated in Appendices K and L, respectively. Using the UNFCCC-CDM method, the baseline emissions for Butler Farms were determined to be 1,015 tCO_2e/yr and the annual project emissions were determined to be 699 tCO_2e/yr, resulting in an emissions reduction of 316 tCO_2e/yr.

For the past several decades, governments and inter-governmental organizations have sought to reduce carbon emissions through monetary incentives. Although the US currently lacks a regulated carbon cap-and-trade system or a carbon tax, GHG offsets are sold by private companies and non-profit organizations to corporations and individuals interested in reducing their net carbon emissions. These offsets are currently being sold for \$10-\$15/tCO_2e *(78-80)*. Between 2003 and 2010 the Chicago Climate Exchange operated the nation's only voluntary, legally binding trading system for GHG emissions. Credits were traded for up to \$7.50/tCO_2e (2008) before the market collapsed and prices were reduced to pennies by 2010 *(81)*. In the European Union (EU), carbon credits have been traded since 2005 in the European Climate Exchange (ECX) to meet emission standards set by the Kyoto Protocol. These EU Allowance Units (EUAs) have a current price (December 3, 2011) of \$10.62 but prices have historically ranged from \$17-\$36/tCO_2e *(82, 83)*. The price of carbon offsets in the ECX is predicted to increase to €30/tCO2e (\$40.20/tCO_2e) by 2020, amended from previous (2008) projections of €53/tCO_2e (\$71.05/tCO_2e) by 2020 *(83)*. The potential revenue for a full scale system at Butler Farms at various carbon offset prices is summarized in Table 20.

Table 20 - Annual revenue from carbon offset sales at Butler Farms. Assumes a carbon reduction of 316 tCO_2e/yr.

Carbon Offset Price (\$/tCO_2e)	Annual Revenue	10-Year Annualized Benefit (\$/1,000 lbs. SSLW)
5	\$1,580	\$1.46
10	\$3,160	\$2.93
15	\$4,740	\$4.39
20	\$6,320	\$5.85
40	\$12,640	\$11.70

6.3.3 Nitrogen Credits

In the past decade, watershed organizations, including two from North Carolina, have experimented with voluntary nitrogen trading programs. Like carbon trading programs, these programs seek to use monetary incentives to reduce nitrogen emissions. Most groups are working towards a cap-and-trade system where total maximum daily loads (TMDLs) would dictate how much nitrogen an entity could emit. Remaining permitted emissions could be sold *(84)*. Establishing and verifying TMDL compliance of non-point sources, such as agricultural sources, has limited the inclusion of non-point sources in preliminary trading *(85)*. Because the TMDL for Butler Farms has not been established, all emissions reductions will be considered for credits, giving a liberal estimate.

Assuming the same performance as the pilot scale system, the effluent from the full scale nitrogen removal system is expected to be 905 mg TN/L, or 5,265 kg TN/year. This is actually an increase from the approximately 800 mg TN/L, or 4,655 kg TN/year, that was emitted from Butler Farms in the liquid waste before the methane capture system was installed. Although the TN in the liquid effluent increases, far less nitrogen is emitted to the atmosphere as ammonia. The nitrogen that volatilizes in an uncovered lagoon remained in the liquid because of the lagoon cover, thus, for the purposes of identifying potential nitrogen credits the nitrogen removed will be the difference between the TN in the covered lagoon and the TN in N tank effluent. The covered anaerobic digester has a total nitrogen concentration of 2,740 mg TN/L (equivalent to emissions of 15,940 kg TN/year), which, assuming a 67% TN reduction (Section 4.5), results in a nitrogen reduction of 10,680 kg TN/year. Although the groups currently developing nitrogen cap-and-trade systems are primarily concerned with nutrients entering local waterways, 10-40% of nitrogen in surface waters can be attributed to ammonia deposition *(61, 86)*.

As the nitrogen trading systems are still developing, credit prices are still being proposed and are highly varied. Proposed prices range from $1-$30/lb. nitrogen removed *(87-89)* giving a wide range of potential monetary benefits (Table 21). A survey of proposed prices and actual trades reveals that most current trading has occurred with a nitrogen price of $1.50-$4/lb. Again, if a cap-and-trade system is developed, revenues will only be a fraction of those listed in Table 21 and are dependent on the TMDLs that are set for the farm. To be conservative, potential benefits from a nitrogen credit cost of $1/lb will be used for cost-benefit analysis.

Table 21 - Potential annual revenue from nitrogen trading credits. Assumes a nitrogen removal of 10,682 kg N/yr.

Nitrogen Credit Price ($/lb N)	Potential Annual Revenue	10-Year Annualized Benefit ($/1,000 lbs. SSLW)
1	$23,550	$21.81
3	$70,649	$65.42
5	$117,749	$109.03
10	$235,498	$218.05
20	$470,996	$436.11
30	$706,493	$654.16

The two voluntary nitrogen trading programs in North Carolina are located in the Tar-Pamlico and Neuse River basins. These programs are part of the North Carolina Ecosystem Enhancement Program (EEP) Nutrient Offset Program established by the North Carolina Department of Environment and Natural Resources. EEP began as a fee-based program, requiring members to pay a fee for nitrogen emissions. The money collected was used to finance best management practices (BMPs) within the watersheds

(90). The price of a nitrogen credit in these basins has varied between \$11 and \$57 per pound of nitrogen *(91)*, and was set at \$28.35 per pound of nitrogen in the Neuse River Basin and \$21.67 per pound of nitrogen in the Tar-Pamlico River Basin in 2007 *(92)*. The Nutrient Offset Program has since changed and is working towards members paying for the actual cost of BMP implementation as opposed to an arbitrary fee.

6.4 Cost-Benefit Analysis

The costs and potential benefits of a full-scale methane capture and nitrogen removal system at Butler Farms were compared for a base-case scenario and for a best-case scenario. Both scenarios were calculated using cost estimates assuming the retrofitting option (Table 22) and cost estimates assuming the construction of new nitrification, denitrification, and storage tanks (Table 23). The base-case scenario assumed a power production conversion factor of 38.2 kWh/ft^3 methane, an electricity cost of \$0.096/kWh, a REC price of \$10/MWh, a carbon offset price of \$10/tCO_2e, and a nitrogen credit price of \$1/lb. N. The best-case scenario assumes a power production conversion factor of 38.2 kWh/ft^3 methane, an electricity cost of \$0.18/kWh, a REC price of \$50/MWh, a carbon offset price of \$40/tCO_2e, and a nitrogen credit price of \$1/lb. N. The assumed cost for nitrogen credits remains low because only a fraction of the calculated TN removal will likely be eligible for trading.

Table 22 - Costs of a full scale system retrofitted for Butler Farms.

	BASE - CASE		BEST CASE	
	10-Year Annualized Cost	10-Year Annualized Cost ($/1,000 lbs. SSLW)	10-Year Annualized Cost	10-Year Annualized Cost ($/1,000 lbs. SSLW)
No Benefits	$159,989	$148.14	$159,989	$148.14
Electricity Savings Only	$150,134	$139.01	$141,511	$131.03
Electricity Savings + RECs	$149,107	$138.06	$136,378	$126.28
Electricity Savings + RECs + Carbon Offsets	$142,787	$132.21	$123,738	$114.57
Electricity Savings + RECs + Carbon Offsets + Nitrogen Credits	$119,237	$110.40	$100,188	$92.77

Table 23 - Costs of a full scale system at Butler Farms that involves the construction of new nitrification, denitrification, and storage tanks.

	BASE - CASE		BEST CASE	
	10-Year Annualized Cost	10-Year Annualized Cost ($/1,000 lbs. SSLW)	10-Year Annualized Cost	10-Year Annualized Cost ($/1,000 lbs. SSLW)
No Benefits	$181,532	$168.09	$181,532	$168.09
Electricity Savings Only	$171,677	$158.96	$163,054	$150.98
Electricity Savings + RECs	$170,650	$158.01	$157,921	$146.22
Electricity Savings + RECs + Carbon Offsets	$164,330	$152.16	$145,281	$134.52
Electricity Savings + RECs + Carbon Offsets + Nitrogen Credits	$140,780	$130.35	$121,731	$112.71

Including all potential benefits, the retrofitted system is expected to cost $110.40/1,000 lbs. SSLW in the average scenario. If a system were currently installed at Butler Farms, the farm could expect to claim the electricity savings and REC sales. The farm could potentially sell carbon offsets, but would need to identify a buyer and would need the credits verified. As nutrient trading markets are still developing, Butler Farms cannot currently claim nitrogen credit benefits.

The values above summarize the financial costs and benefits for the farmer. The Smithfield Agreement requires ESTs to be economically feasible, but there has been disagreement among members of the economic subcommittee as to the meaning of 'economic feasibility.' Traditionally, economic feasibility accounts for the costs and benefits to society while financial feasibility only incudes the costs and benefits for a particular stakeholder. Some members of the subcommittee argued that a technology would be infeasible if the cost was greater than the cost of a lagoon and sprayfield system because additional costs could reduce the size of the NC swine herd and put the NC swine industry at a disadvantage relative to other states. In an attempt to quantify societal benefits from improved waste management systems, the economic subcommittee decided that a technology could cause a 12% reduction in the NC swine herd and still be considered economically feasible. A 12% reduction was determined to be allowable because the NC General Assembly had previously passed regulations that were predicted to reduce the swine herd by 12%. The economic subcommittee determined that a technology with a cost of \$89/1,000 lbs. SSLW (2005 \$) would cause a herd reduction of 12%. In comparison, even the best-case scenario for the proposed integrated energy recovery and nitrogen removal system would not be considered economically feasible.

6.5 Additional Benefits

In addition to the benefits mentioned in Section 6.3, a full-scale methane capture and nitrogen removal system would provide non-monetary benefits and potential monetary benefits beyond the scope of this report. The covered lagoon and nitrogen removal system dramatically reduces gaseous ammonia emissions. The lagoon covers prevent ammonia in the lagoon from volatilizing, and the nitrogen removal system removes up to 95% of ammonia, preventing it from being volatilized during land application. Atmospheric ammonia has been linked to respiratory health problems and even infant mortality. It has been suggested that a 50% removal of ammonia would provide $189 million per year in health benefits in North Carolina *(19)*. The reduction of ammonia emissions from swine farms can drastically reduce state atmospheric ammonia concentrations as up to 46% of atmospheric ammonia in North Carolina comes from swine farms *(93)*.

A reduction in ammonia emissions will also translate to a reduction of nitrogen in regional surface waters from the deposition of atmospheric ammonia. As discussed in 6.3.3, atmospheric ammonia deposition can account for 10-40% of N in surface waters *(61, 86)*. Heavy nutrient loading on lakes, streams, and estuaries can lead to eutrophication, fish kills, and aesthetic concerns if the water is used for drinking water.

Although odor was not quantified in this study, the odor at Butler Farms was virtually eliminated by the installation of the lagoon covers. The effluent from the nitrification and denitrification tanks had very little odor. State regulations require new swine waste management facilities to have a dilution-to-threshold ratio of less than or equal to 7:1 when using a field olfactometry method and instrumentation, or to have an observed instantaneous odor intensity less than the equivalent of 225 ppm n-butanol when using an Odor Intensity Referencing Scale *(102)*. Odors from swine farms have been found to decrease the enjoyment derived from surrounding properties and have decreased property values *(1, 10, 94)*. A 2005 study found a decrease of 8% in median home value for properties located one mile from swine farms *(94)*.

Tom Butler reports that the addition of the lagoon covers at his farm have improved the ease of waste management. Without the collection of rainwater in the lagoons, he was less concerned about the possibility of large storms filling lagoons past permitable limits or causing leaks or other structural damage. These advantages would not be realized, however, for the nitrogen removal and effluent storage components of the proposed integrated system, as these components would not be covered.

7.0 CONCLUSIONS

The combined methane capture and nitrogen removal system was found to reduce ammonium emissions in liquid effluent by at least 80% and often by greater than 95%. This allows the technology to meet the state regulations for an EST. Appendices K and L predict full scale ammonia emissions from the N and D tanks to be 0.0022 kg NH_3-N/wk/1000 kg SSLW and 0.000018 kg NH_3-N/wk/1000 kg SSLW, respectively, for the high emissions scenarios. Assuming all ammonium in the liquid effluent was volatilized as ammonia during spraying, ammonia emissions from land application is only 0.07 kg NH_3-N/wk/1000 kg SSLW. This assumes a high effluent ammonium concentration of 297 mg NH_4^+-N/L, the mean pilot scale effluent concentration plus one standard deviation. Although barn emissions were not quantified, it is nearly certain that farm emissions do not exceed 0.9 kg NH_3-N/wk/1000 kg SSLW, treatment and storage emissions do not exceed 0.2 kg NH_3-N/wk/1000 kg SSLW, and land application emissions do not exceed 0.2 kg NH_3-N/wk/1000 kg SSLW, the state limits for an EST. The quantified predicted farm emissions are only 0.07 kg NH_3-N/wk/1000 kg SSLW.

The proposed system also meets the EPS for an 80% reduction in ammonia required for Smithfield Agreement ESTs, but does not consistently achieve the Smithfield Agreement performance standard of 75% removal of TN when compared to the baseline farm. While the combined methane capture and nitrogen removal system was found to reduce ammonia emissions, the total nitrogen in the liquid waste was not reduced. However, due to the increased total nitrogen concentrations in a covered anaerobic lagoon, a covered lagoon should not be operated without a subsequent nitrogen removal system.

Although odor was not quantified in this study, it is likely that the system meets the odor EPS. This study did not quantify the other EPSs imposed by the NC General Assembly and the Smithfield Agreement.

The full-scale system at base-case assumptions was found to be similar in cost to the ESTs investigated through the Smithfield Agreement (Table 1). Potential monetary benefits do not make the technology financially feasible for Butler Farms without assistance. State cost-sharing programs exist to cover up to 90% of construction costs, but with the present assumptions annual costs still exceed annual benefits *(15)*.

8.0 Future Work

The pilot-scale system experienced a number of operation difficulties which may have led to removal rates not representative of those that could, potentially, be achieved. The pilot-scale system was largely operated using a single HRT for nitrification and denitrification and a single recycle ratio. Future studies could experiment with smaller HRTs to determine the smallest HRT that does not cause a decrease in nitrogen removal. Municipal waste water treatment plants typically use a solids retention time for nitrification of ten days and three days for denitrification. A smaller HRT would lead to a decrease in the nitrification and denitrification tank volume, reducing the cost of the system.

The parameters used for system design and cost and benefit estimation were extrapolated from a pilot-scale system and thus have the potential to deliver inaccurate full-scale performance and cost estimates. Many assumptions were made to complete full-scale design and cost estimates. The construction and operation of a full-scale system, as was done with the majority of Smithfield Agreement technologies, would provide a more accurate measure of the system's performance and cost. The operation of a full-scale system could provide more data on the actual demand for sodium carbonate, potentially reducing operation costs

A significant portion of the capital and operation costs comes from the construction and operation of the N tank aeration system. The use of an anaerobic ammonia oxidation (Anammox) system for nitrogen removal would reduce these costs by using nitrite as the electron acceptor. The Anammox process was identified in the 1990s, but has not been applied to hog waste treatment *(95)*. Further development of the Anammox technology could lead to more economically feasible nitrogen removal.

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APPENDIX A – PILOT-SCALE REACTOR OPERATION SUMMARY OF EVENTS

- 7/22/10 – Fill the tanks with activated sludge, water, and lagoon effluent.
- 7/30/10-8/3/10 – Pumps were run during the day but would crash and turn off overnight. Low DO in the N tank.
- 8/4/10-9/2/10 – Peristaltic pumps remained off in an attempt to increase the DO in the N tank. DO remained 0.1-0.3 mg/L for this month. pH in the N tank would frequently drop below 7 and there was moderate sodium carbonate pumping.
- 9/3/10 – D tank was drained and refilled with water. A new oxygen infuser was installed in the N tank. Peristaltic pumps remained off.
- 9/5/10 – DO increased to 5 mg/L.
- 9/6/10-9/9/10 – Peristaltic pumps remained off but DO continued to increase.
- 9/10/10 – Started peristaltic pumps
- 9/11/10-10/5/10 – Peristaltic pumps were operating but frequently crashed. DO was very high (in the 20s) and we were pumping ~1L/min of oxygen.
- 9/30/10-10/1/10 – pH in both N and D tanks dropped.
- 10/5/10 – Barns being cleaned for new pigs.
- 10/13/10 – Sodium carbonate pumping pH set-point set at 6.8
- 10/15/10-11/3/10 – Sodium carbonate pumped nearly every day
- 11/9/10 – Submersible pump in N tank broke, not noticed until 11/11/10
- 11/11/10 – Pigs are sick and medicine going into water.
- 11/11/10-11/15/10 – Peristaltic pumps remain off because no mixing in N tank
- 11/15/10 – Submersible pump replaced and peristaltic pumps restarted at 9pm. Top was removed from N tank.
- 11/17/10-11/28/10 – Sodium carbonate pumped
- 12/6/10 – Tubing was switched between MCD2 and MCD3.
- 12/6/10-12/16/10 – D tank was nearly emptied (<300L liquid) as liquid was pumped from D tank to N tank. N tank volume increased. D tank recirculation line off 12/12/10-12/13/10 because too little liquid in D tank for it to pump. Corrected 12/16/10.
- 12/23/10 – Took top off D tank to scrub sides.
- 12/31/10-1/19/11 – oxygen flow rate was 0.45 L/min or less. It was 0.2 L/min on 1/5/11 and 1/6/11. Did not return to 0.6 L/min or higher until 1/20/11.
- 1/29/11-2/2/11 – A modest amount of sodium carbonate (10-15L) was pumped daily. pH hovered around 6.88.
- 2/13/11-2/18/11 – N and D tank volumes unstable. Changing flow rates a lot.
- 3/8/11-3/10/11 – Very difficult to read tank volumes, sludge accumulation.
- 3/15/11 – Pigs out of our lagoon's barns.
- 3/30/11 – New delivery of pigs to our barns.
- DO low (<5mg/L): 10/24/10-11/1/10, 11/4/10-11/19/10, 11/24/10-26/10, 12/12/10-12/14/10, 12/21/10-12/23/10, 1/27/11-1/29/11, 2/7/11, 2/9/11-2/10/11, 2/15/11, 2/18/11-2/22/11, 3/1/11-3/7/11, 3/10/11, 3/19/11, 4/3/11-4/5/11, 4/12/11

APPENDIX B – PILOT SCALE DATA

This appendix shows the variation in nitrogen species concentrations during the course of pilot-plant operation. All values are reported as 30-day running averages to smooth daily variation and identify trends. 30-day running average reported for a given day was calculated by averaging the data for the 30 days prior to that day. The nitrite and nitrate concentrations in the N and D tanks varied widely during reactor operation. It is not known how much of this variation can be attributed to operating conditions, seasonal changes in the lagoon liquid, or other factors. Variability of ammonium, nitrite and nitrate concentrations in the N and D tanks is displayed in Figures B3 and B4. Ammonium concentrations in the D tank were greater than those in the N tank because liquid from the lagoon was being pumped into the D tank. In the N tank ammonium was converted to nitrite and nitrate explaining the higher concentration of those species in the N tank. In the D tank nitrite and nitrate were denitrified to nitrogen gas. In the last months of the project we saw near complete denitrification.

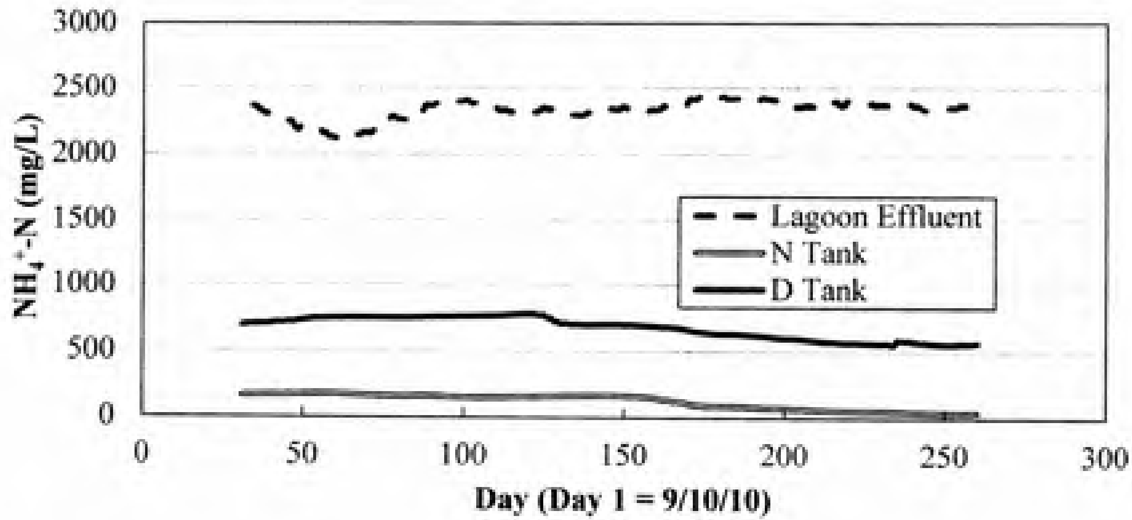


Figure B1 - 30-day running average of ammonium-N concentration in lagoon effluent, N tank and D tank between 9/10/10 and 5/27/11.

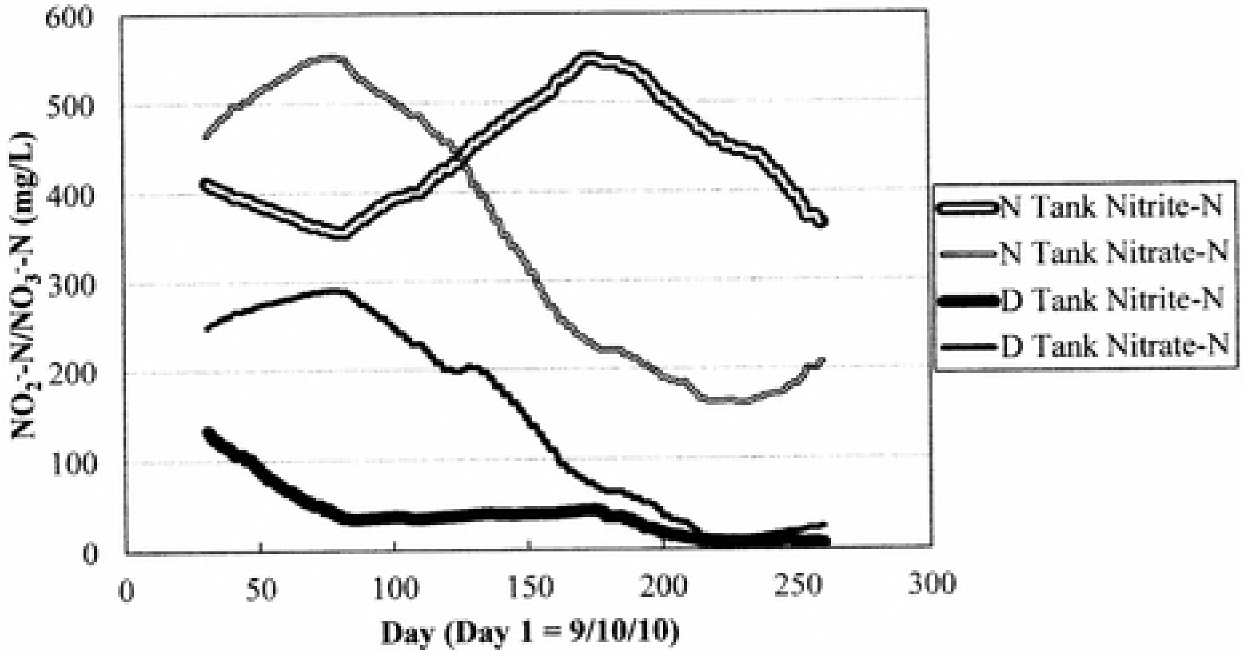


Figure 13 - 30-day running average of nitrite-N and nitrate-N concentration in the N and D tanks between 9/10/10 and 5/27/11.

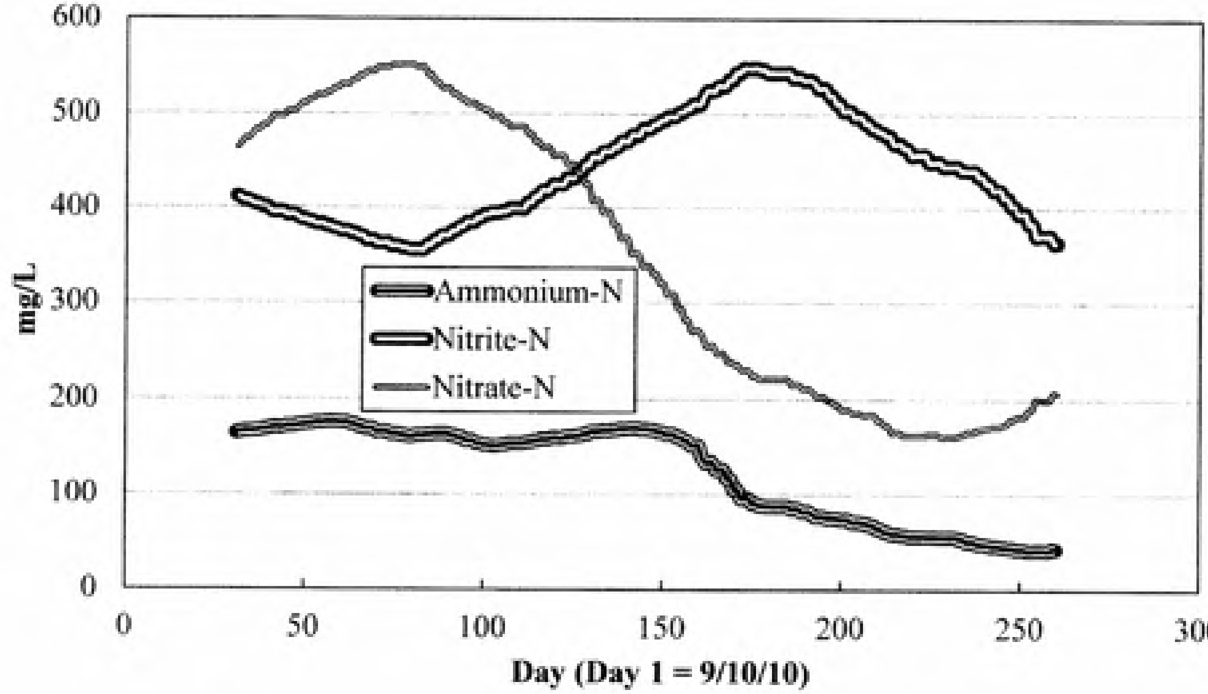


Figure B3 - 30-day running average of inorganic N species concentrations in the N tank between 9/10/10 and 5/27/11.

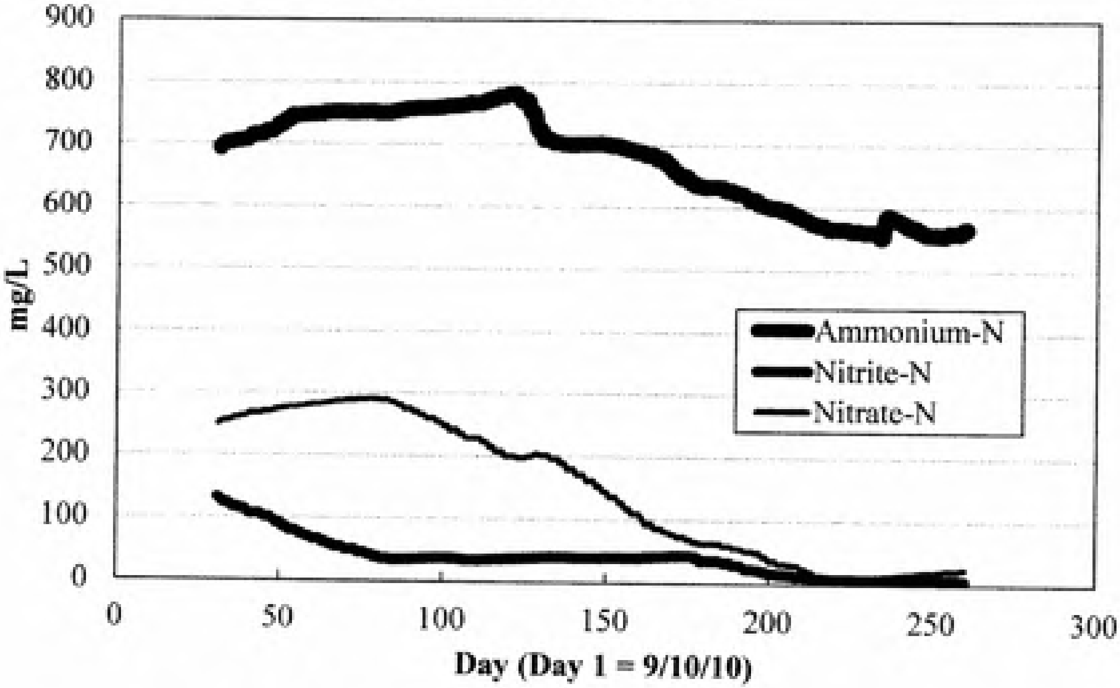


Figure B4 - 30-day running average of inorganic N concentrations in the D tank between 9/10/10 and 5/27/11.

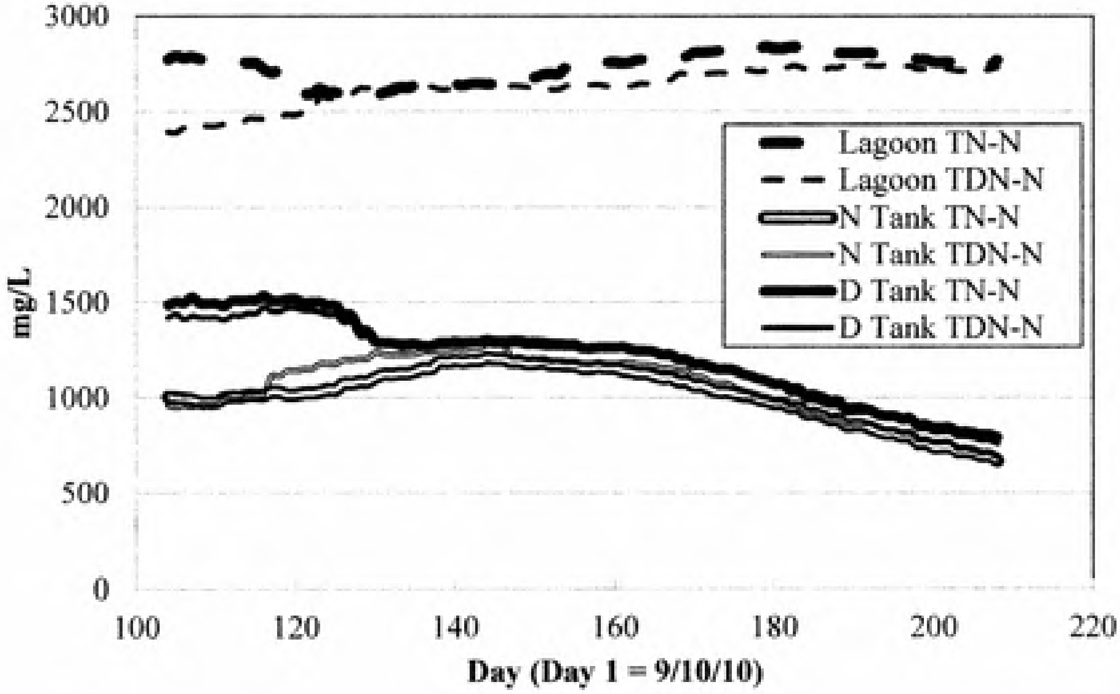


Figure B5 - 30-day running average of TN and TDN concentrations in the lagoon effluent, N tank and D tank.

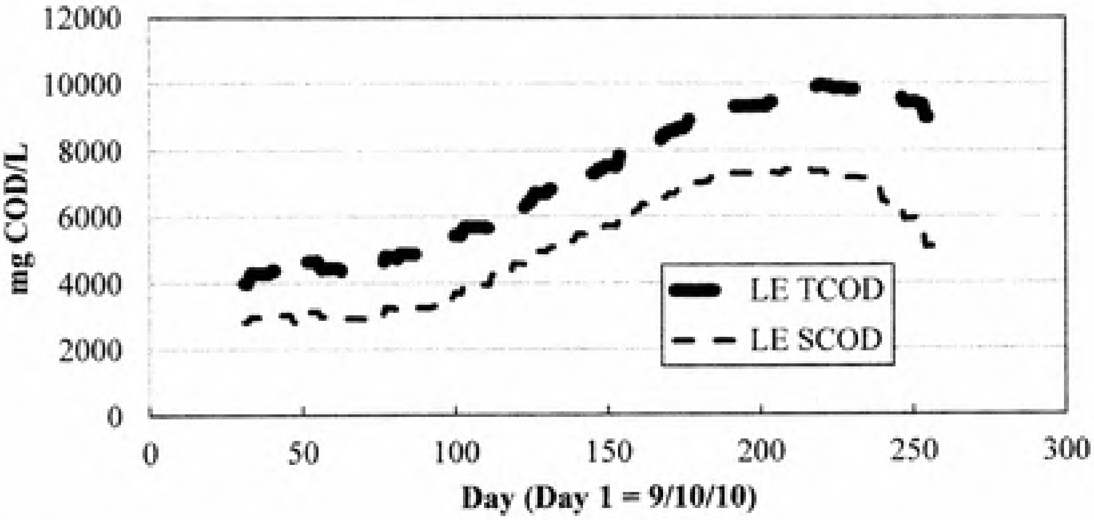


Figure B6 - 30-day running average of total and soluble COD in the lagoon effluent between 9/10/10 and 5/27/11.

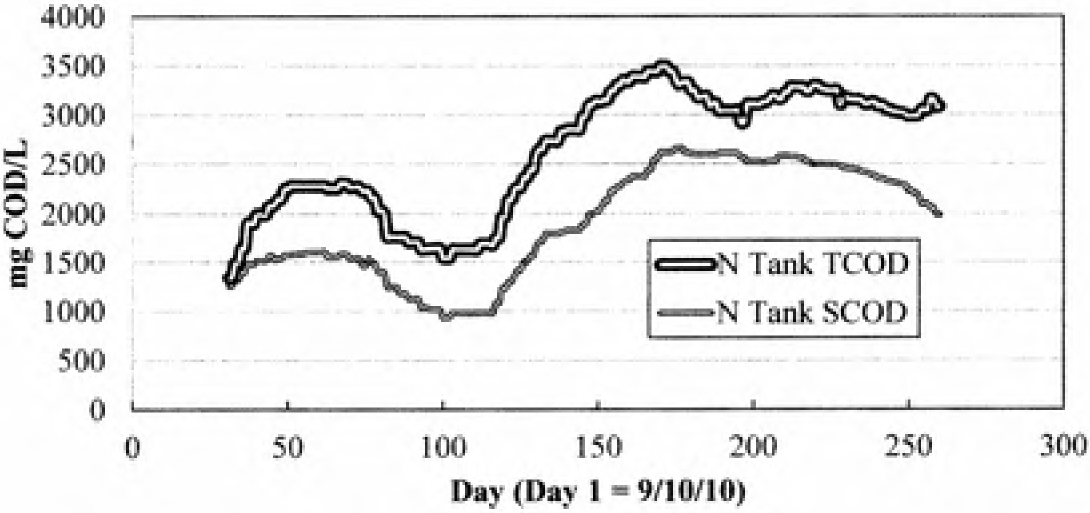


Figure B7 - 30-day running average of total and soluble COD in the N tank effluent between 9/10/10 and 5/27/11.

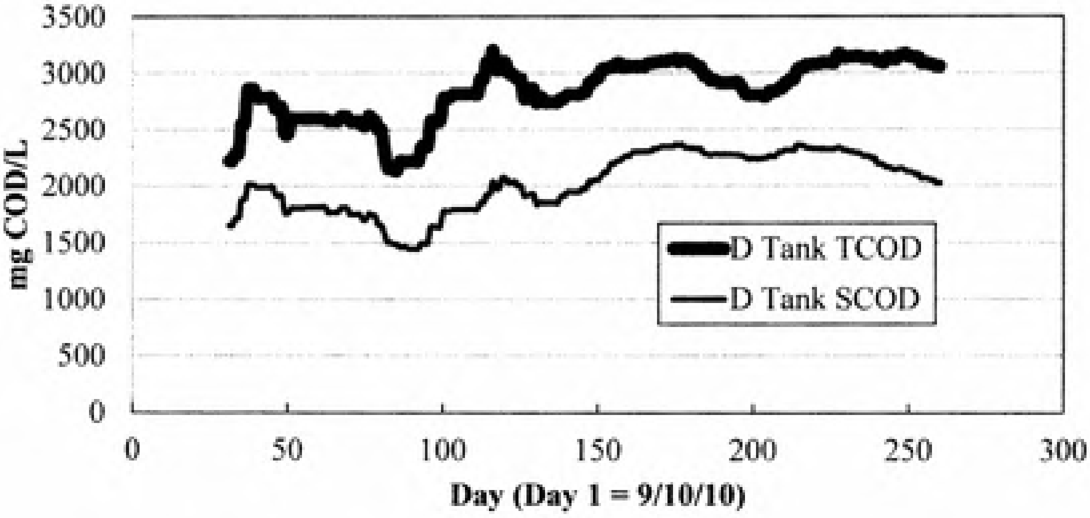


Figure B8 - 30-day running average of total and soluble COD in the D tank effluent between 9/10/10 and 5/27/11.

APPENDIX C – FULL SCALE NITRIFICATION/DENITRIFICATION TANK DESIGN – SCHEME B

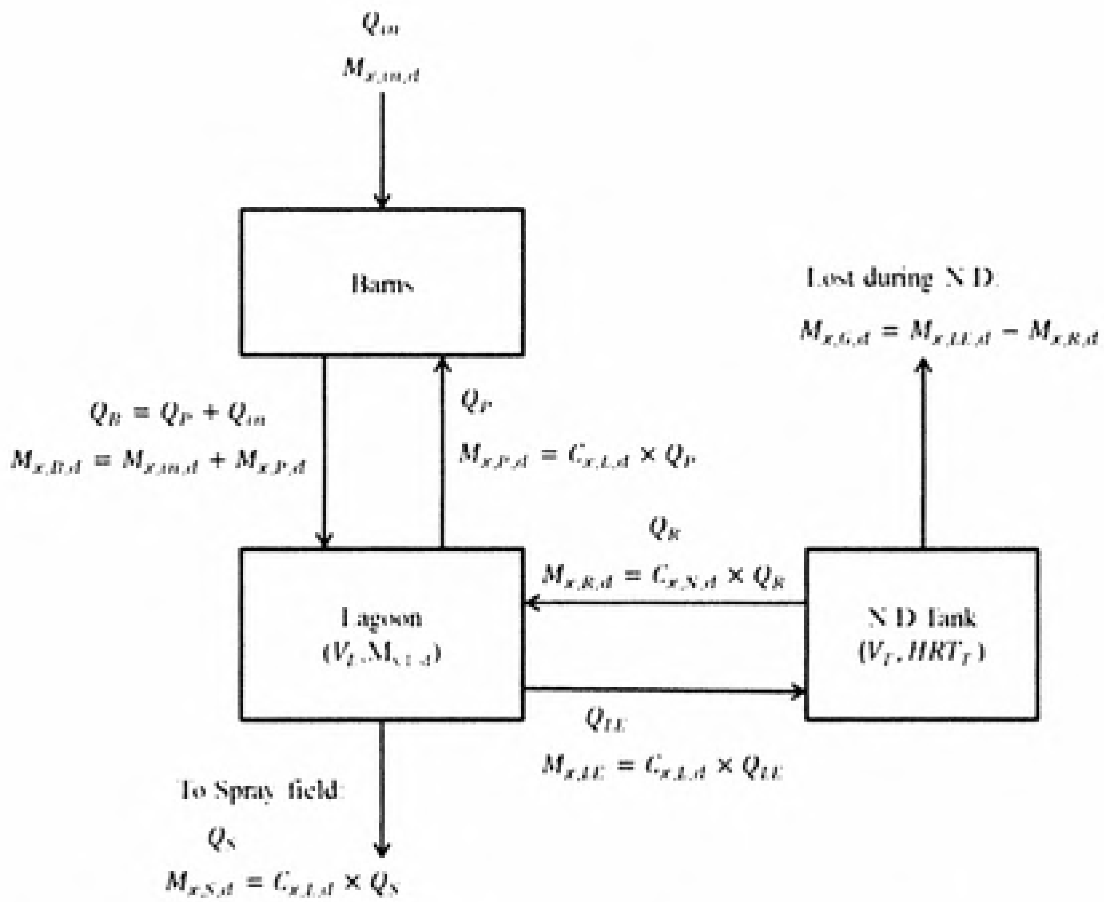


Figure C1 – Mass balance model of any species "x" in full-scale system - Scheme B.

Where:

Q_{in} = liquid flow rate into system from hog waste, spilled drinking water, sprinkler water and barn-washing water

$M_{x,in}$ = mass of species x entering system from hog waste

Q_B = flow rate of liquid flushed from barn waste collection pits to lagoon

$M_{x,B,d}$ = mass of species x entering lagoon from barn waste collection pits on day d

V_L = volume of lagoon

$M_{x,L,d}$ = mass of species x in lagoon on day d

Q_{LE} = flow rate of liquid from lagoon into nitrification/denitrification system (D tank)

$M_{x,LE,d}$ = mass of species x entering nitrification/denitrification system (D tank) from lagoon on day d

$C_{x,L,d}$ = concentration of species x in lagoon on day d

$M_{x,G,d}$ = mass of species x exiting nitrification/denitrification system in gaseous form on day d

V_T = combined liquid volume of N and D tanks

HRT_T = combined hydraulic retention time of N and D tank

Q_R = flow rate of liquid from the nitrification/denitrification system (N tank) to lagoon

$M_{x,R,d}$ = mass of species x entering lagoon from the nitrification/denitrification system (N tank) on day d

$C_{x,N,d}$ = concentration of species x in N tank on day d

Q_P = flow rate of liquid from the lagoon to the barn waste collection pits

$M_{x,P,d}$ = mass of species x entering barn waste collection pits from lagoon on day d

Q_S = flow rate of liquid from the lagoon to spray fields

$M_{x,S,d}$ = mass of species x applied to spray field on day d

Assumptions:

$Q_{in} = 15{,}940\ L/day$

$M_{NH_4^+-N,in} = 37.3 \dfrac{kg_{NH_4^+-N}}{day}$

$Q_{in} = Q_{LE} = Q_R = Q_S{}^{*}$

$Q_P = 227{,}100\ L/day\ (60{,}000\ gal/day)^{**}$

$V_L = 41{,}640{,}000\ L\ (11{,}000{,}000\ gal)$

$C_{NH_4^+-N,L,0} = 2{,}340\ \frac{mg_{NH_4^+-N}}{L}$

$C_{NH_4^+-N,N} = 165\ \frac{mg_{NH_4^+-N}}{L}$

$V_T = 658{,}400\ L$

$HRT_T = 41.3\ days$

Model assumes no loss of any species "x" in the barns.

*For simplicity and because annual spray patterns cannot be predicted, Q_S will be assumed equal to Q_{in}.

**Pit refill volume required alternates between 151,400 L (40,000 gal) and 302,800 L (80,000 gal) each day.

Ammonia was modeled in Scheme B (Figure C1) using a mass balance of ammonia in the lagoon.

$$M_{NH_4^+-N,L,d} = M_{NH_4^+-N,L,d-1} - \left(M_{NH_4^+-N,S,d} + M_{NH_4^+-N,P,d} + M_{NH_4^+-N,LE,d}\right) + \left(M_{NH_4^+-N,R,d} + M_{NH_4^+-N,B,d}\right)$$

$$C_{NH_4^+-N,L,d} = \frac{M_{NH_4^+-N,L,d}}{V_L}$$

The lagoon ammonia concentration over time using the assumptions above (means) is plotted below (Figure C2). Also included are high and low estimations.

High estimation:

$C_{NH_4^+-N,L,0} = 2{,}500\ \frac{mg_{NH_4^+-N}}{L}$

$C_{NH_4^+-N,N} = 250\ \frac{mg_{NH_4^+-N}}{L}$

Low estimation:

$$C_{NH_4^+-N,L,0} = 2{,}200 \frac{mg_{NH_4^+-N}}{L}$$

$$C_{NH_4^+-N,N} = 0 \frac{mg_{NH_4^+-N}}{L}$$

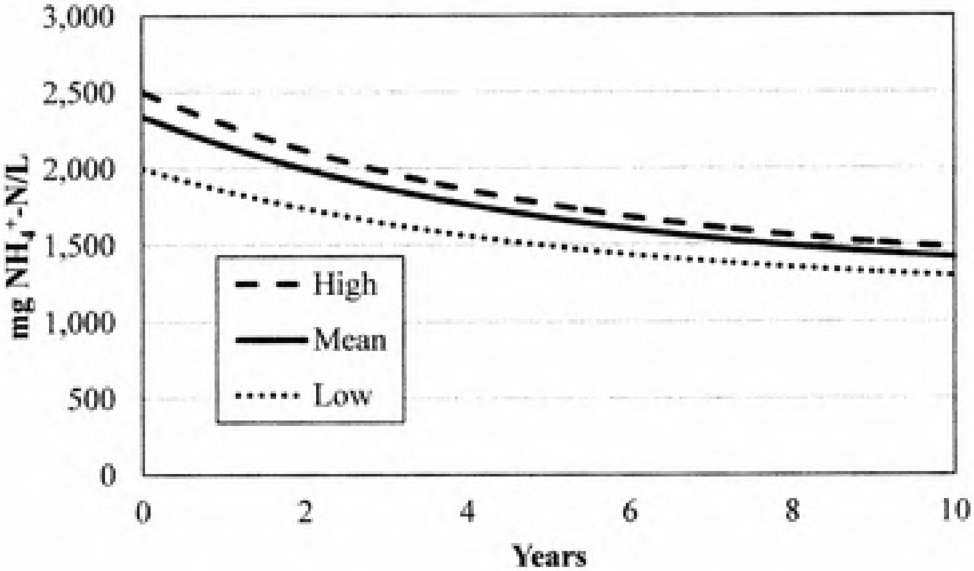


Figure C2 - Estimation of NH_4^+-N concentration in lagoon over time in Scheme B.

After 10 years the ammonium-N concentration in the lagoon fails to be reduced to N-tank concentrations or even halved. Because lagoon liquid is used to refill the barn pits and for land application, more ammonia will volatilize and be applied to land than desired.

For the ammonium-N concentration in the lagoon to be reduced more quickly, the flow rate to (and from) the nitrification/denitrification system must be increased. Continuing to use an HRT_T of 41.3 days and increasing the flow rate will require larger N and D tanks, increasing the cost of the system. Figure C3 displays lagoon ammonium-N concentrations at different Q_{LE} and Q_R flow rates using $C_{NH_4^+-N,L,0} = 2{,}340\frac{mg_{NH_4^+-N}}{L}$ and $C_{NH_4^+-N,N} = 156\frac{mg_{NH_4^+-N}}{L}$.

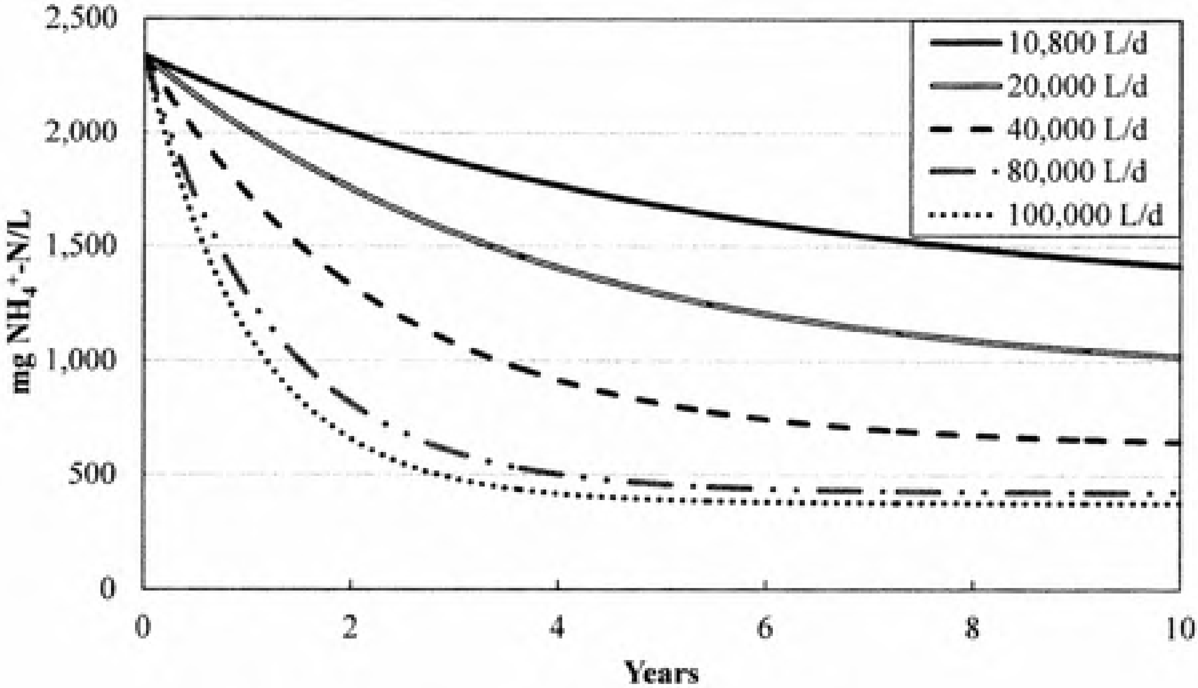


Figure C3 - Sensitivity analysis of QLE and QR on lagoon ammonia concentration.

Despite an increase in Q_{LE} and Q_R to 100,000 L/d, the steady-state lagoon ammonium-N concentration is only $377\frac{mg}{L}$, and does not approach this value for five years. The required nitrification/denitrification system volume for each of the above flow rates is shown in Table C1. The larger the tank required, the higher the capitol and operating costs of the system.

Table C1 - Nitrification/denitrification design volume required for flow rates Q_{LE} and Q_R assuming a HRT_T of 41.3 days.

Q_{LE}, Q_R	V_T Required
10,800	446,040
20,000	826,000
40,000	1,652,000
80,000	3,304,000
100,000	4,130,000

APPENDIX D - FULL SCALE NITRIFICATION/DENITRIFICATION TANK MODELING – SCHEME C

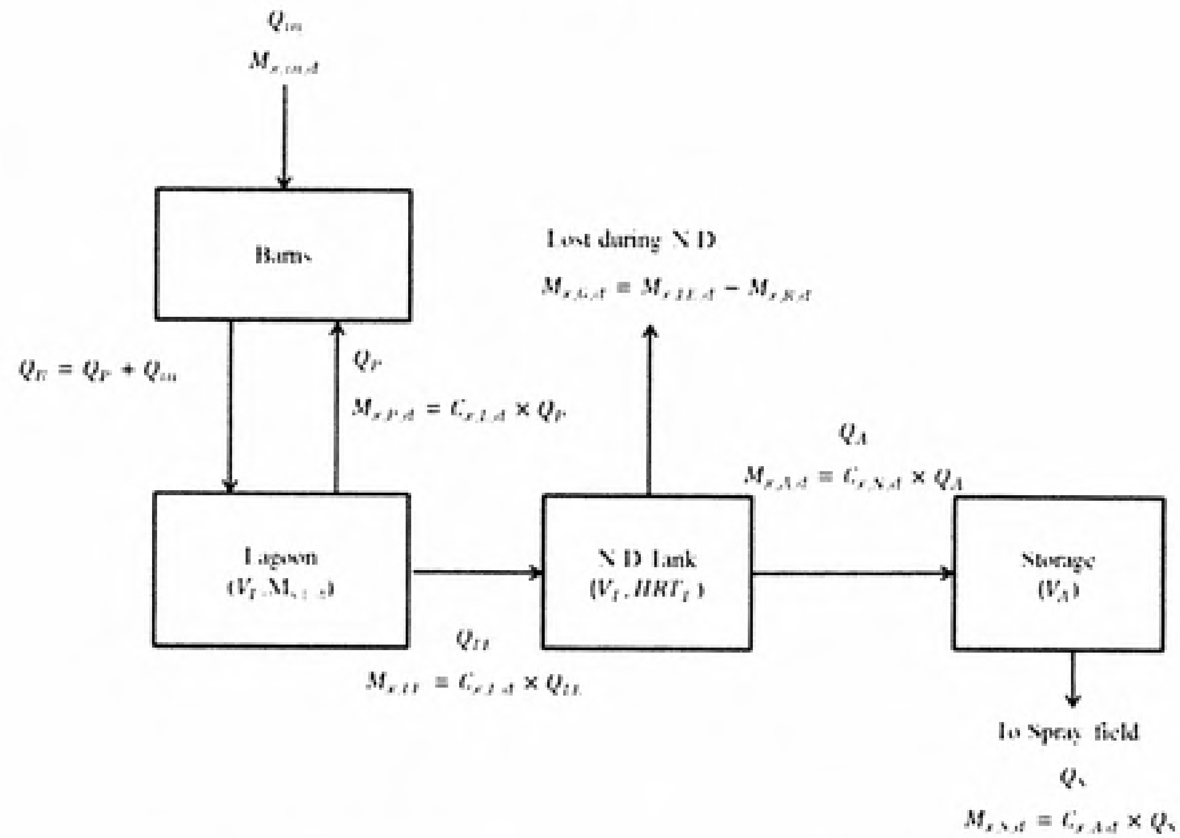


Figure D1- Model of species x in full scale system - Scheme C.

Where:

Q_{in} = liquid flow rate into system from hog waste, spilled drinking water, sprinkler water and barn-washing water

$M_{x,in}$ = mass of species x entering system from hog waste

Q_B = flow rate of liquid flushed from barn waste collection pits to lagoon

$M_{x,B,d}$ = mass of species x entering lagoon from barn waste collection pits on day d

V_L = volume of lagoon

$M_{x,L,d}$ = mass of species x in lagoon on day d

Q_{LE} = flow rate of liquid from lagoon into nitrification/denitrification system (D tank)

$M_{x,LE,d}$ = mass of species x entering nitrification/denitrification system (D tank) from lagoon on day d

$C_{x,L,d}$ = concentration of species x in lagoon on day d

$M_{x,G,d}$ = mass of species x exiting nitrification/denitrification system in gaseous form on day d

V_T = combined liquid volume of N and D tanks

HRT_T = combined hydraulic retention time of N and D tank

Q_A = flow rate of liquid from the nitrification/denitrification system (N tank) to storage

$M_{x,A,d}$ = mass of species x entering storage from the nitrification/denitrification system (N tank) on day d

$C_{x,N,d}$ = concentration of species x in N tank on day d

Q_P = flow rate of liquid from the lagoon to the barn waste collection pits

$M_{x,P,d}$ = mass of species x entering barn waste collection pits from lagoon on day d

Q_S = flow rate of liquid from the lagoon to spray fields

$M_{x,S,d}$ = mass of species x applied to spray field on day d

Assumptions:

$$Q_{in} = 15{,}940\ L/day$$

$$M_{NH_4^+-N,in} = 37.3\frac{kg_{NH_4^+-N}}{day}$$

$$Q_{in} = Q_{LE} = Q_A$$

$$Q_P = 227{,}100\ L/day\ (60{,}000\ gal/day)^{**}$$

$V_L = 41{,}640{,}000\ L\ (11{,}000{,}000\ gal)$

$C_{NH_4^+-N,L,0} = 2{,}340\ \frac{mg_{NH_4^+-N}}{L}$

$C_{NH_4^+-N,N} = 165\ \frac{mg_{NH_4^+-N}}{L}$

$V_T = 445{,}700\ L$

$HRT_T = 41.3\ days$

**Pit refill volume required alternates between 151,400 L (40,000 gal) and 302,800 L (80,000 gal) each day.

Appendix E – Price Adjustment

All monetary costs and benefits were adjusted to 2011 dollars using the Consumer Price Index (CPI-U) as reported by the U.S. Department of Labor Bureau of Labor Statistics. The values used reflect annual averages among all commodities and all U.S. cities where CPI is measured. Since an annual average CPI-U for 2011 was not yet available, the most recent monthly CPI-U (February 2011) was used.

To determine the conversion factor (CF) necessary to convert prices to 2011 dollars, the CPI-U for each year was divided by the CPI-U for 2011 (Table E1). To convert a price to 2011 dollars, the price is divided by the CF. Example: $100 (2004)/0.8536 = $117.20 (2011)

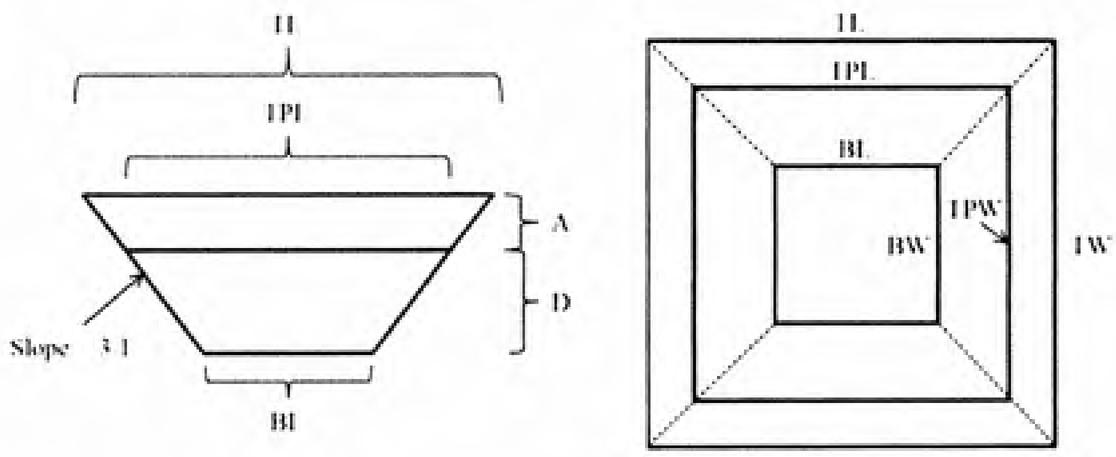
Table E1 - Consumer Price Index (CPI-U) and conversion factors used to adjust costs and returns to 2011 dollars.

Year	CPI-U	CF (2011)
1990	130.7	0.5906
1991	135.2	0.6109
1992	140.3	0.6340
1993	144.5	0.6529
1994	148.2	0.6697
1995	152.4	0.6886
1996	156.9	0.7090
1997	160.5	0.7252
1998	163.0	0.7365
1999	166.6	0.7528
2000	172.2	0.7781
2001	177.1	0.8002
2002	179.9	0.8129
2003	184.0	0.8314
2004	188.9	0.8536
2005	195.3	0.8825
2006	201.6	0.9109
2007	207.342	0.936889
2008	215.303	0.972861
2009	214.537	0.969400
2010	218.056	0.985301
2011	221.309	1.000000

APPENDIX F – FULL SCALE NITRIFICATION/DENITRIFICATION TANK AND STORAGE TANK SIZING AND COSTS – EARTHEN CONTAINMENT STRUCTURE

Nitrification/Denitrification Tank

At full scale, nitrification and denitrification can be designed as an earthen containment structure similar to that used for lagoons. The nitrification and denitrification zones will be housed in the same structure with a curtain to separate the two zones. The earthen containment structures will be designed as a trapezoidal hexahedron with a rectangular base (BW by BL), the most common design for swine waste lagoons. As shown in Figure F1, the basin will be filled with liquid to a design depth D. The liquid will have a surface area of TPL (top permanent length) by TPW. The basin will have sides with a 3:1 slope (horizontal:vertical). NRCS specifications require the slope to be less than 1:1 *(50)*.



a.) Side view b.) Top view

Figure F1 - Earthen containment structure diagram.

The design volume (PV), 26,040 ft^3, was calculated in Section 4.3.2 using the assumed flow rate into the nitrification/denitrification system (563 ft^3/d) and the system's HRT (41.3 days). The volume of the trapezoidal hexahedron was calculated by dividing the basin into one cube, four triangular prisms (sides) and four pyramids (corners). The permanent liquid volume (PV) can be calculated using as follows:

$$PV = \gamma(BW)^2(D) + (1+\gamma)(3)(D^2)(BW) + (12)(D^3)$$

The base width (BW) and base length (BL) are related using the ratio γ.

$$\gamma = \frac{BL}{BW}$$

The nitrification/denitrification tank was designed with a square base so BL=BW and γ=1. A liquid depth of 10 feet was assumed which is consistent with the depth of the existing lagoons at Butler Farm (10 feet and 12 feet). The necessary BW is calculated using the assumed design volume and liquid depth:

$$BW = \frac{-(1+\gamma)(3)(D^2) + \sqrt{(1+\gamma)^2(9)(D^4) - (4)(\gamma)(D)[(12)(D^3) - PV]}}{(2)(\gamma)(D)}$$

$$BW = \frac{-(1+1)(3)(10^2) + \sqrt{(1+1)^2(9)(10^4) - (4)(1)(10)[(12)(10^3) - 26{,}040]}}{(2)(1)(10)}$$

The base will have a width and length of 18 feet and an area of 324 square feet. Assuming that the slope of the sides is 3:1 and that BW=BL, the TPW and TPL can be calculated:

$$TPW = TPL = BW + (2)(3)(D) = 18 + (2)(3)(10) = 78$$

Unlike the lagoon, the nitrification/denitrification basin will not be covered so an emergency storage volume must be added to the top of the basin. In North Carolina the average annual rainfall minus the average annual evaporation is 10 inches. The added depth must be equal to or greater than two 24-hour, 25-year rainfall events as per the NRCS standards. In Harnett County a 24-hour, 25-year storm is 7 inches *(96)*. The NRCS standards also require an additional structural freeboard to prevent spills, suggesting one foot of additional depth for open structures. The total additional depth (A) assumed in the design of the nitrification/denitrification basin is three feet. The total volume of the basin (V), including the additional depth is 48,828 ft^3 (1,808 yd^3):

$$V = \gamma(BW^2)(D + A) + (1 + \gamma)(3)[(D + A)^2](BW) + (12)[(D + A)^3]$$

$$V = 1(18^2)(10 + 3) + (1 + 1)(3)[(10 + 3)^2](18) + (12)[(10 + 3)^3] = 48{,}828$$

The top length (TL) and top width (TW) of the basin, including the additional depth are 96 feet:

$$TW = TL = BW + (2)(3)(D + A)$$

$$TW = TL = 18 + (2)(3)(10 + 3) = 96$$

The cost of constructing an earthen containment structure is a function of the volume of the basin. Excavation costs are priced per cubic yard excavated and vary with the volume of earth excavated. The assumed example excavation costs used by Zering (adjusted to 2011 dollars) are shown in Table F1 *(51)*.

Table F1 - Excavation costs assumed by Zering

Volume Excavated (Cubic Yards)	Excavation Cost ($)
1,000	3.82
10,000	3.63
20,000	3.42
30,000	3.22
40,000	3.03
50,000	2.86
60,000	2.69
70,000	2.53
80,000	2.38
90,000	2.24
100,000	2.11
150,000	1.58

The excavation of a trapezoidal hexahedron does not typically require excavation of the entire basin volume. Contractors will take advantage of the landscape and will build up the walls of the basin with the excavated earth. Studies have assumed that between 70% and 100% (for rectangular prisms) of the designed volume is excavated. Zering's assumption of 70% was adopted for estimating cost.

Because the design volume is between entries in Table F1, the unit cost is found through linear interpolation (Figure F2).

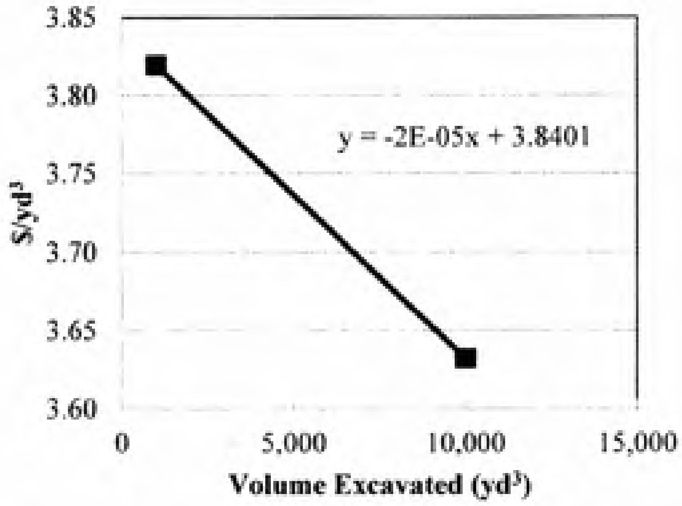


Figure F2 - Linear interpolation of earthen containment structure excavation costs.

The unit cost for excavation is a function of the designed volume:

$$Unit\ cost(\$) = (V \times -0.00002) + 3.8401$$

The unit cost for excavation for the nitrification/denitrification system is $\$3.80/yd^3$ and the cost of excavation is \$4,815:

$$Cost(\$) = (V \times 0.70) \times Unit\ cost(\$)$$

Excavation costs for the storage basin were also calculated using this method (see below). When both the N/D system and the storage basin are earthen containment structures, the total excavation volume is 7,774 yd^3 and a unit cost of \$3.68 can be used.

In this case, the cost of the N/D basin excavation is $4,659. This excavation cost does not include overhead charges, which are included in the construction costs used to calculate the overhead cost.

Storage Tank

The storage tank is designed and priced using the same assumptions and formulas as used above for the N/D basin. The design volume (PV), 102,801 ft^3, was calculated in section 5.5 by designing the storage tank as an equalization tank. As with the N/D tank, a liquid depth of 10 feet was assumed which is consistent with the depth of the existing lagoons at Butler Farm (10 feet and 12 feet). Again, an additional three feet of depth (A) will be added to the design depth – two feet to meet emergency rainfall storage requirements and one foot for structural freeboard (see above). The base of the basin will have a width (BW) and length (BL) of 70 feet and an area of 4,900 square feet. The total volume of the basin (V), including the additional depth is 161,044 ft^3 and the top length (TL) and top width (TW) of the basin, including the additional depth are each 148 feet.

Construction costs assume that only 70% of the design volume will be excavated (see above) and use the unit price assumptions provided in Table F1 and Figure F2. The unit cost for excavation for the storage tank is $3.72/yd3 and the cost of excavation is $15,535. The total excavation volume for the N/D tank and storage tank can be combined (7,774 yd3) to reduce the unit cost to $3.68/yd3 and the total excavation cost to $15,365. $3.68 can be used. This excavation cost does not include overhead charges and is included in the construction costs used to calculate the overhead cost.

Appendix G – Earthen Containment Structure Lining Costs

Earthen containment structures must be lined to prevent the liquid from escaping the basin and from compromising the structure walls. Liners are often either clay or plastic, though North Carolina requires ESTs to use plastic liners *(102)*.

Clay Liner

The cost of a clay liner is based on the volume of clay needed and is highly dependent on the amount of clay that must be imported to the site. When farms are located in areas with clay soil, less clay must be imported from another location. Butler Farms does not have clay soil and must import 100% of the clay used for liners *(37)*.

Liners are designed to be 1.5 feet thick with this thickness measured perpendicular to the sloped walls of the structure. Where the sloped walls meet the bottom of the tank, the clay thickness will be greater, 1.58 feet (assuming the walls have a 3:1 slope). See the technical report on the Barham Farm technology *(51)* for detailed calculations of corner angles and the resulting corner clay thickness. The liner of the entire base of the tank will have a thickness of 1.58 feet. The volume of clay needed is calculated using the designed dimensions of the earthen containment structure as the interior measurements. The volume of clay needed (V_{liner}) is the volume of the tank (V_{tank}) subtracted from the volume of the tank with the liner ($V_{w/liner}$). This volume is increased by 15% to account for the compaction of the clay.

$$V_{w/liner} = \gamma(BW)^2(D + A + 1.50) + (1 + \gamma)(3)((D + A + 1.58)^2)(BW) + (12)((D + A + 1.58)^3)$$

$$V_{liner} = \left(V_{w/liner} - V_{tank}\right)(1.15)$$

$$V_{liner} = (64{,}849 - 48{,}828)(1.15) = 18{,}424\ ft^3$$

These equations use variables used in the design of the earthen containment structures in Appendices F and K. The unit cost of clay is assumed to be \$5.50/yd^3, though it can range from \$4.40/yd^3 to \$6.00/yd^3 *(51)*. The cost and volume of clay needed for the N/D tank and the storage tank are listed below (Table G1). These costs will be included in the construction cost used to calculate the 20% overhead.

Table G1 - Cost of clay liner for earthen containment structures. V_{liner} includes 15% for compaction.

	V_{liner}	Cost
N/D Tank	682	\$3,753
Storage Tank	1,554	\$8,546

Plastic Liner

The cost of a plastic liner is based on the surface area of material needed and additional fees (Table G2).

Table G2 - Plastic liner installation costs *(51)*.

Fee	Cost
Initialization fee	\$4,686
Liner fee	\$0.38/ft^2
Penetration fee	\$352/penetration
Non-slide surface	\$1,617

The initialization fee can be divided among projects if more than one basin on a farm is being lined. The earthen containment structures were found to be the most cost-effective solution for the N/D system and the storage tank so a \$2,000 initialization fee will be used when calculating the lining cost of each. This initialization fee can also be reduced if multiple farms in an area line their basins at the same time. The plastic liner area is calculated using variables from the design of the earthen containment structures (Appendix F).

$$Plastic\ liner\ area = \gamma(BW)^2 + (2 + 2\gamma)(BW)\left(10^{1/2}\right)(D + A) + 12\left(10^{1/2}\right)(D + A)^2$$

An additional 8% is added to the surface area for anchoring *(51)*. The N/D system is assumed to require six penetrations and the storage tank is assumed to have two penetrations. Penetrations are locations where influent and effluent pipes pass through the liner. The liner must be sealed around each pipe that penetrates the liner. Every basin must have a non-slide surface that allows someone who falls into the tank to climb out. The cost estimates of plastic liners for the N/D system and storage tank are shown below (Table G3). These costs are included in the construction cost used to calculate the 20% overhead.

Table G3 - Area of material needed and cost of plastic liners. Area includes an additional 8% for anchoring.

	Area (ft^2)	Cost
N/D Tank	10,473	$9,995
Storage Tank	24,650	$15,310

Although plastic liners were found to be more expensive, subsequent design and cost estimates assume the use of a plastic liner.

APPENDIX H – FULL SCALE NITRIFICATION/DENITRIFICATION TANK SIZING AND COSTS - CONCRETE CONTAINMENT STRUCTURE

The N/ D tank and storage tank can be designed as concrete containment structures. The structure is assumed to be rectangular with non-sloping sides, a design depth, D, and a permanent volume, PV. The base will have an area of BW x BL. The base width (BW) is proportional to the base length (BL):

$$BW = \gamma \times BL$$

For the N/D tank and storage tank the BW and BL are assumed equal ($\gamma = 1$). As with the earthen containment structures, three feet of additional depth (A) will be added to the design depth. This will account for one foot of freeboard and two feet for emergency storage and rainwater.

$$BL = \sqrt{\frac{PV}{\gamma(D + A)}}$$

The concrete walls will have a thickness, TW, of six inches. The total excavation volume and the total concrete volume are calculated below:

$$Excavation\ volume = (BW + 2TW)(BL + 2TW)(D + A)$$

$$Volume\ concrete = Excavation\ volume - BW(BL)(D + A)$$

A four-inch layer of sand and six-inch layer of gravel will be located below the finished structure. The volume of gravel required is:

$$Volume\ gravel = (BW + 2TW)(BL + 2TW)(0.5)$$

and the volume of sand required is:

$$Volume\ sand = (BW + 2TW)(BL + 2TW)(0.33)$$

Forms are required for the construction of the basin walls and are priced by wall surface area.

$$Area\ of\ wall\ forms = 4\ walls \times (BW)(D + A)$$

Reinforcement bars will be spaced ever 12 inches along the length and width of the basin (includes the basin walls and basin floor).

$$Length\ of\ reinforcement\ bars$$
$$= 2\frac{bars}{ft} \times \{(BW + 2TW)(BL + 2TW) + (4)(BW)(D + A)\}$$

The concrete floor must be finished with a finishing slab. The cost of finishing is based on the area to be finished and only includes the basin floor:

$$Area\ to\ be\ finished = (BW + 2TW)(BL + 2TW)$$

Unit prices for each of these costs are shown in Table H1.

Table H1 - Unit costs of concrete containment structure *(51)*.

Unit	Price
Ready mix concrete	\$74.63/yd^3
Gravel fill (6")	\$11.20/yd^3
Sand fill (4")	\$56.88/yd^3
Wall form work	\$5.74/ft^2
Wall reinforcement bars	\$0.53/ft
Finishing slab (concrete)	\$0.39/ft^2

The N/D tank will have a BW and BL of 43 feet and a total depth (D+A) of 13 feet. The storage tank will have a BW and BL of 89 feet and a total depth of 13 feet. The quantity of materials and costs of the N/D tank and the storage tank are displayed below in Table H2.

Table H2 - Materials needed and costs of N/D and storage concrete containment structures.

	Material	Quantity Needed	Cost
N/D Tank	Ready mix concrete	42 yd^3	\$3,075
	Gravel fill	35 yd^3	\$389
	Sand fill	23 yd^3	\$1,303
	Wall form work	2200 ft^2	\$12,624
	Wall reinforcement bars	13897 ft	\$7,327
	Finishing slab (concrete)	1874 ft^2	\$724
		Total:	**\$25,441**
Storage Tank	Ready mix concrete	87 yd^3	\$6,427
	Gravel fill	150 yd^3	\$1,677
	Sand fill	99 yd^3	\$5,622
	Wall form work	4625 ft^2	\$26,546
	Wall reinforcement bars	37516 ft	\$19,778
	Finishing slab (concrete)	8087 ft^2	\$3,126
		Total:	**\$63,176**

APPENDIX I – BAFFLE DESIGN AND COSTS

The baffle used to separate the N tank from the D tank (and from the storage tank in the Butler Farms-specific retrofitting alternative) will be made from the same HDPE material used to cover the lagoon. The cost for the baffles is based on the area (SA) needed and estimated using the unit price estimate Zering used from Environmental Fabrics (converted to 2011 dollars). For areas up to 20,000 ft^2, the price is \$1.87/ft^2 and for areas 140,000 ft^2 and greater, the price is \$1.05/ft^2. For areas between 20,000 ft^2 and 140,000 ft^2 the unit price is interpolated from these two points:

$$Unit\ Cost\ \left(\frac{\$}{ft^2}\right) = \frac{(140{,}00 - SA)(\$1.87)}{120{,}000} + \frac{(SA - 20{,}000)(\$1.05)}{120{,}000}$$

These prices include the cost of extra material needed for anchoring the baffles in their respective tanks. If the design were implemented at a new farm, the lagoon covers and the baffles would be installed at the same time so a unit cost reflecting that of the entire project is used - \$1.05/ft^2. The area of material needed in each alternative is assumed to be equal to the cross-sectional area of each of the tanks. Prices for each of the proposed baffles are show in Table I1.

Table I1 - Surface area required and cost of baffles for each alternative.

Alternative	SA (ft^2)	Cost
N/D Earthen Containment Structure	741	\$778
N/D Concrete Containment Structure	550	\$578
N/D Steel Tank	864	\$907
Butler Farm-Specific Retrofitting	5,460	\$5,733

This cost is included in the construction cost used to calculate the 20% overhead.

APPENDIX J – FULL-SCALE NITRIFICATION/DENITRIFICATION TANK SIZING AND COSTS - STEEL TANK

The nitrification/denitrification system and the storage tank can be designed as steel tanks. For consistency, this report uses the tank distributor and cost estimates used in Zering's report for the Super Soils technology. The tanks used in his estimate are manufactured by Engineered Storage Products Company in DeKalb, IL and are distributed in Bailey, NC by Brock Equipment Company. The cylindrical tanks are constructed from steel rings mounted together on a concrete base. The rings are made from a varying number of sheets of steel, depending on the tank size. Zering's tank sizing and cost tables as provided by Engineered Storage Products Company and Brock Equipment Company are converted to 2011 dollars below (Tables J1 and J2). The tank (or tank combination) that meets the design volume requirements (V_T, V_N, V_D or V_A) for the lowest cost was selected.

Table J1 - Volume (gallons) of Engineered Storage Products Company Tanks (51).

Number of sheets/ring	Diameter (ft.)	2 Rings	3 Rings	4 Rings	5 Rings	6 Rings
3	8	3,900	5,800			
4	11		10,400			
5	14		16,300	21,600	26,800	32,100
6	17		23,500	31,100	38,700	46,200
7	20	21,700	32,000	42,300	52,600	63,000
8	22		41,800	55,300	68,800	82,300
9	25		52,900	70,000	87,000	104,100
10	28		65,300	86,400	107,500	128,500
11	31		79,100	104,600	130,100	155,500
12	34		94,100	124,500	154,800	185,100
13	36		110,500	146,100	181,700	217,300
14	39		128,100	169,400	210,700	252,000
15	42		147,100	194,500	241,900	289,300
16	45		167,400	221,300		
17	48		188,900	249,800		
18	50	143,600	211,800	280,100		
19	53		236,000	312,100		
20	56		261,500	345,800		
21	59	195,400	288,300	381,200		
22	62		316,400	418,400	520,400	622,300
23	64		345,900	457,300		
24	67		376,600	498,000		
25	70	277,000	408,600	540,300		
26	73		442,000	584,400		
27	76		476,700	630,200		
28	78	347,400	512,600	677,800		
29	81		549,900	727,100	904,200	1,081,400

Table J2 - Cost of Engineered Storage Products Company Tanks adjusted to 2011 dollars *(51)*.

Number of sheets/ring	Diameter (ft.)	2 Rings	3 Rings	4 Rings	5 Rings	6 Rings
3	8	$7,689	$8,055			
4	11		$11,990			
5	14		$11,130	$14,744	$16,792	$20,965
6	17		$14,018	$17,811	$23,915	$28,209
7	20	$15,370	$19,221	$23,578	$29,805	$35,967
8	22		$22,559	$27,369	$33,992	$40,519
9	25		$25,989	$31,167	$37,655	$44,501
10	28		$29,499	$34,970	$41,319	$38,938
11	31		$33,080	$38,779	$44,982	$34,072
12	34		$36,538	$42,690	$48,646	$79,872
13	36		$39,886	$46,692	$52,309	$90,643
14	39		$43,139	$50,772	$55,973	$92,047
15	42		$45,923	$53,908	$63,301	$72,379
16	45		$49,999	$57,751		
17	48		$54,074	$61,594		
18	50	$50,006	$58,148	$65,437		
19	53		$60,736	$70,069		
20	56		$63,324	$74,703		
21	59	$54,253	$65,912	$79,336		
22	62		$75,488	$87,930	$103,499	$121,139
23	64		$78,634	$92,714		
24	67		$81,780	$97,499		
25	70	$68,398	$84,926	$102,284		
26	73		$88,813	$107,074		
27	76		$92,700	$111,864		
28	78	$78,937	$96,587	$116,654		
29	81		$107,091	$129,165	$158,754	$190,142

According to Zering, these costs reflect those likely to occur on a typical NC farm, but some variation is to be expected. These costs do not include tax, labor costs and materials for piping and plumbing work. Additional charges can be expected for each penetration of the tank.

The N/D system was priced using one-, two- and three-tank alternatives. The storage tank was priced using one- and two-tank alternatives (Table J3).

Table J3 - Cost and size of selected tanks for N/D and storage tank alternatives.

Alternative	Tank	Design Volume (gal)	Provided Volume (gal)	No. of rings	Rings/ sheet	Cost
N/D - combined N/D tank	-	173,910	181,700	5	13	**$52,309**
N/D - 1 N tank, 1 D tank	N Tank	139,128	147,100	3	15	$45,923
	D Tank	34,782	41,800	3	8	$22,559
					Total:	**$68,482**
N/D - 2 N tanks, 1 D tank	N Tank 1	139,128	70,000	4	9	$31,167
	N Tank 2		70,000	4	9	$31,167
	D Tank	34,782	41,800	3	8	$22,559
					Total:	**$84,893**
Storage - 1 tank	-	769,005	904,200	5	29	**$158,754**
Storage - 2 tanks	Tank 1	769,005	408,600	3	25	$84,926
	Tank 2		381,200	4	21	$79,336
					Total:	**$164,262**

The one-tank solutions were the lowest price alternative for both systems. The combined N/D tank will require a baffle separating the N tank liquid from the D tank liquid. The cost of this baffle (Appendix I) is $907, resulting in a total talk cost of $53,216.

Appendix K - Method to Calculate Oxygen Consumption and Gas Production in Nitrification Tank

Oxygen consumption rates and greenhouse gas production rates for the full-sized system are based on observed rates of the pilot scale system. Gases in the nitrification and denitrification tanks in the pilot-scale system were regularly sampled from the tank's headspace and measured for CO_2, CH_4, N_2O and NH_3 using a gas chromatograph beginning November 26, 2010 (Table K1).

Table K1 - Measured quantities of gases in pilot-scale N tank headspace (percent by volume).

Date	CO_2	CH_4	N_2O	NH_3
11/26/10	42.0	0.02	0.81	
12/10/10	35.7	0.02	0.56	
01/19/11	52.0	0.05	0.88	
01/26/11	35.1	0.04	0.90	
02/09/11	45.5	0.02	0.68	
02/17/11	38.3	0.02	1.00	
02/23/11	32.6	0.01	0.72	
03/02/11	16.2	0.01	0.43	0.0003
03/08/11	no data	0.01	0.89	0.0009
03/23/11	44.4	0.01	0.84	0.0015
03/29/11	35.3	0.01	0.67	0.0003
04/05/11	49.8	0.01	0.82	0.0004
04/13/11	46.5	0.01	0.85	0.0001
04/19/11	40.5	0.01	0.92	0.0006
04/27/11	44.1	0.01	1.11	0.0006
05/04/11	29.0	0.01	0.61	0.0001
05/10/11	37.4	0.01	0.72	0.0007
05/18/11	29.5	0.20	0.46	0.0001

For the N tank, because there was no independent measurement of the off-gas flow rate, the off-gas flow rate was estimated from the known O_2 inflow rate to the N tank, estimated O_2 consumption in the N tank, and production of other gases in the N tank. The reactor operating conditions and influent/effluent liquid characteristics were averaged for the gas sampling day and the seven preceding days.

The mass of oxygen pumped into the nitrification tank each day ($M_{O_2,in,d}$) was calculated using the oxygen flow rate on that day ($\mathrm{Q_{O_2,in,d}}$) and corresponding trailer temperature ($T_{t,d}$) with the ideal gas law.

$$M_{O_2,in,d} = \frac{P \times \mathrm{Q_{O_2,in,d}}}{R \times (273.15 + T_{t,d})} \times \frac{1440\ minutes}{day} \times \frac{31.9988\ g\ O_2}{mol\ O_2}$$

Where:

$M_{O_2,in,d}$ = Mass of oxygen pumped into nitrification tank in day d (g)

P = Atmospheric pressure (assumed 1 atm)

$\mathrm{Q_{O_2,in,d}}$ = Oxygen flow rate into nitrification tank on day d (L/min)

R = Ideal gas constant (assume 0.0821L atm K^{-1} mol^{-1})

$T_{t,d}$ = Temperature in trailer on day d (degrees C)

The concentrations of nitrogen species were used to estimate the mass of nitrite and nitrate produced from each liter of lagoon effluent. First the nitrite ($r_{NO_2^- -N,d}$) and nitrate ($r_{NO_3^- -N,d}$) ratios were calculated:

$$r_{NO_2^- -N,d} = \frac{C_{NO_2^- -N,N,d}}{C_{NO_2^- -N,N,d} + C_{NO_3^- -N,N,d}}$$

$$r_{NO_3^- -N,d} = \frac{C_{NO_3^- -N,N,d}}{C_{NO_2^- -N,N,d} + C_{NO_3^- -N,N,d}}$$

Where:

$C_{NO_2^- -N,N,d}$ = Concentration of NO_2-N in the nitrification tank effluent on day d (mg/L)

$C_{NO_3^- -N,N,d}$ = Concentration of NO_3-N in the nitrification tank effluent on day d (mg/L)

The mass of nitrite, nitrate and ammonium as nitrogen in the nitrification tank effluent does not equal the mass of ammonium as nitrogen entering the N/D system because both nitrite and nitrate were removed in the D tank. Instead, the mass of nitrite ($M_{NO_2^- -N,p,d}$) and nitrate ($M_{NO_3^- -N,p,d}$) produced per liter of lagoon effluent (mg/L) on day d is calculated by multiplying the nitrite and nitrate ratios by the difference between the mass of ammonium as nitrogen entering and leaving the N/D system on day d. This assumes that what enters the system on day d corresponds to what leaves the system on day d. This assumption can be made due to the limited variation in lagoon effluent ammonium concentration. I also assumed that all inorganic nitrogen in the lagoon effluent is in the form of ammonium.

$$M_{NO_2^- -N,p,d} = \left(M_{NH_4^+ -N,in,d} - M_{NH_4^+ -N,N,d}\right) \times r_{NO_2^- -N,d}$$

$$M_{NO_3^- -N,p,d} = \left(M_{NH_4^+ -N,in,d} - M_{NH_4^+ -N,N,d}\right) \times r_{NO_3^- -N,d}$$

The oxygen flow rate, influent ammonium masses, nitrite produced, nitrate produced, and influent flow rate (MCD1) are averaged for the seven days prior to the gas sampling day. Results are shown in Table K2.

Table K2 - Average influent LE flow rate, O_2 flow rate, LE NH_4^+-N concentration, and produced NO_2^--N and NO_3^--N on gas sampling days*

Date	MCD1 (L/D)	O_2 Flow Rate (g/d)	NH_4^+-N Conc (mg/L)	NO_2^--N Produced (mg/L)	NO_3^--N Produced (mg/L)
11/26/2010	58	1,142	2,465	527	1,873
12/10/2010	66	1,209	2,347	25	2,251
1/19/2011	69	956	2,264	457	1,347
1/26/2011	56	1,113	2,278	589	1,153
2/9/2011	47	1,192	2,381	1,542	681
2/17/2011	48	1,343	2,380	1,409	790
2/23/2011	49	1,619	2,391	1,537	717
3/2/2011	49	1,752	2,563	1,694	325
3/8/2011	50	2,506	2,391	1,543	634
3/16/2011	51	1,409	2,338	1,562	664
3/23/2011	51	1,297	2,199	1,696	426
3/29/2011	52	1,312	2,470	1,725	684
4/5/2011	53	1,242	2,306	1,794	420

*Influent LE flow rates are adjusted MCD1 flow rates. The mass flow rate of oxygen was calculated using volumetric flow rates and the corresponding indoor air temperature for that day. All values represent averages of the available data for the gas sample day and the seven days prior to the sampling day.

For every mole of ammonium converted to nitrite, 1.5 moles of oxygen are consumed.

For every mole of ammonium converted to nitrate, two moles of oxygen are consumed.

$$NH_4^+ + 1.5O_2 \rightarrow H_2O + NO_2^- + 2H^+$$

$$NO_2^- + 0.5O_2 \rightarrow NO_3^-$$

$$Net: NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

To calculate the oxygen consumed for ammonia oxidation to nitrite ($M_{O_2,NO_2^-,d}$), the mass of nitrite produced per liter of LE was multiplied by the stoichiometric oxygen to ammonium ratio and the LE flow rate:

$$M_{O_2,NO_2^-,d} = \frac{C_{NO_2^- -N,p,d} \times \frac{g}{1000\ mg}}{14.01 \frac{g\ NO_2^- - N}{mol\ NO_2^- - N}} \times \frac{1.5\ mol\ O_2}{1\ mol\ NO_2^- - N} \times \frac{31.9988\ g\ O_2}{mol\ O_2} \times Q_{LE,d}$$

Likewise, to calculate the oxygen consumed for ammonia oxidation to nitrate ($M_{O_2,NO_3^-,d}$), the mass of nitrate produced per liter of LE is multiplied by the stoichiometric oxygen to ammonium ratio and the LE flow rate:

$$M_{O_2,NO_3^-,d} = \frac{C_{NO_3^- - N,p,d} \times \frac{g}{1000\ mg}}{14.01 \frac{g\ NO_3^- - N}{mol\ NO_3^- - N}} \times \frac{2.0\ mol\ O_2}{1\ mol\ NO_3^- - N} \times \frac{31.9988\ g\ O_2}{mol\ O_2} \times Q_{LE,d}$$

Where:

$Q_{LE,d}$ = Daily flow rate of lagoon effluent to the N/D system (L/d)

$M_{O_2,NO_2^-,d}$ = Mass of O_2 consumed during ammonia oxidation on day d (g)

$M_{O_2,NO_3^-,d}$ = Mass of O_2 consumed during nitrite oxidation on day d (g)

The molar mass of nitrogen is assumed to be 14.01 g/mole and the molar mass of oxygen is assumed to be 15.9994 g/mole. The total mass of oxygen consumed per day (g), $M_{O_2,c,d}$, is the sum of the oxygen required for ammonia oxidation and for nitrite oxidation:

$$M_{O_2,c,d} = M_{O_2,NO_2^-,d} + M_{O_2,NO_3^-,d}$$

The difference between the mass of oxygen pumped into the system and the theoretical mass of oxygen consumed is the mass of oxygen in the N tank off-gas ($M_{O_2,N,d}$). This does not account for heterotrophic consumption of oxygen, which, for simplicity, is assumed negligible.

$$M_{O_2,N,d} = M_{O_2,in,d} - M_{O_2,c,d}$$

The CO_2, CH_4, N_2O and NH_3 measured in the N tank off-gas were reported as a percent of the gas by volume. It is assumed that oxygen makes up the remainder of the off-gas volume.

$$X_{O_2,N,d} = 100 - X_{CO_2,N,d} + X_{CH_4,N,d} + X_{N_2O,N,d} + X_{NH_3,N,d}$$

Where:

$X_{O_2,N,d}$ = Percent O_2 in N tank off-gas on day d

$X_{CO_2,N,d}$ = Percent CO_2 in N tank off-gas on day d

$X_{CH_4,N,d}$ = Percent CH_4 in N tank off-gas on day d

$X_{N_2O,N,d}$ = Percent N_2O in N tank off-gas on day d

$X_{NH_3,N,d}$ = Percent NH_3 in N tank off-gas on day d

The known mass of oxygen in N tank off-gas is used to determine the mass of CO_2, CH_4, N_2O and NH_3 produced. Because the gas was sampled from the N-tank headspace, the indoor air temperature corresponding to the gas sampling day is used to convert between mass and volume.

$$PV = nRT$$

$$V_{O_2,N,d} = \frac{M_{O_2,N,d}}{2\frac{mol\ O}{mol\ O_2} \times 15.9994\frac{g\ O}{mol\ O}} \times R \times T_{t,d} \times \frac{1}{P}$$

$$V_{G,N,d} = \frac{V_{O_2,N,d}}{\left(\frac{X_{O_2,N,d}}{100}\right)}$$

$$V_{CO_2,N,d} = \left(\frac{X_{CO_2,N,d}}{100}\right) \times V_{G,N,d}$$

$$V_{CH_4,N,d} = \left(\frac{X_{CH_4,N,d}}{100}\right) \times V_{G,N,d}$$

$$V_{N_2O,N,d} = \left(\frac{X_{N_2O,N,d}}{100}\right) \times V_{G,N,d}$$

$$V_{NH_3,N,d} = \left(\frac{X_{NH_3,N,d}}{100}\right) \times V_{G,N,d}$$

$$M_{CO_2,N,d} = \frac{P \times V_{CO_2,N,d}}{R \times T_{t,d}} \times \frac{44.0098\ g\ CO_2}{mol\ CO_2}$$

$$M_{CH_4,N,d} = \frac{P \times V_{CH_4,N,d}}{R \times T_{t,d}} \times \frac{16.04276\ g\ CH_4}{mol\ CH_4}$$

$$M_{N_2O,N,d} = \frac{P \times V_{N_2O,N,d}}{R \times T_{t,d}} \times \frac{44.01288\ g\ N_2O}{mol\ N_2O}$$

$$M_{NH_3,N,d} = \frac{P \times V_{NH_3,N,d}}{R \times T_{t,d}} \times \frac{17.031\ g\ NH_3}{mol\ NH_3}$$

Where:

$V_{O_2,N,d}$ = Volume of O_2 in N tank off-gas on day d (L)

R = Ideal gas constant (assume 0.0821L atm K^{-1} mol^{-1})

$T_{t,d}$ = Temperature in trailer on day d (degrees C)

P = Atmospheric pressure (assumed 1 atm)

$V_{CO_2,N,d}$ = Volume of CO_2 in N tank off-gas on day d (L)

$V_{CH_4,N,d}$ = Volume of CH_4 in N tank off-gas on day d (L)

$V_{N_2O,N,d}$ = Volume of N_2O in N tank off-gas on day d (L)

$V_{NH_3,N,d}$ = Volume of NH_3 in N tank off-gas on day d (L)

$M_{CO_2,N,d}$ = Mass of CO_2 in N tank off-gas on day d (g)

$M_{CH_4,N,d}$ = Mass of CH_4 in N tank off-gas on day d (g)

$M_{N_2O,N,d}$ = Mass of N_2O in N tank off-gas on day d (g)

$M_{NH_3,N,d}$ = Mass of NH_3 in N tank off-gas on day d (g)

The mass of O_2 consumed per gram of NH_4^+-N and the mass of CO_2, CH_4, N_2O and NH_3 produced per gram NH_4^+-N per day is determined by dividing the masses consumed or produced by the ammonium entering the N/D system.

$$Y_{O_2,N,d} = \frac{M_{O_2,c,d}}{C_{NH_4^+-N,LE,d} \times \frac{g}{1000\ mg} \times Q_{LE,d}}$$

$$Y_{CO_2,N,d} = \frac{M_{CO_2,N,d}}{C_{NH_4^+-N,LE,d} \times \frac{g}{1000\ mg} \times Q_{LE,d}}$$

$$Y_{CH_4,N,d} = \frac{M_{CH_4,N,d}}{C_{NH_4^+-N,LE,d} \times \frac{g}{1000\ mg} \times Q_{LE,d}}$$

$$Y_{N_2O,N,d} = \frac{M_{N_2O,N,d}}{C_{NH_4^+-N,LE,d} \times \frac{g}{1000\ mg} \times Q_{LE,d}}$$

$$Y_{NH_3,N,d} = \frac{M_{NH_3,N,d}}{C_{NH_4^+-N,LE,d} \times \frac{g}{1000\ mg} \times Q_{LE,d}}$$

Where:

$Y_{O_2,N,d}$ = Mass O_2 consumed per gram NH_4^+-N entering N/D on day d (g)

$Y_{CO_2,N,d}$ = Mass CO_2 produced per gram NH_4^+-N entering N/D on day d (g)

$Y_{CH_4,N,d}$ = Mass CH_4 produced per gram NH_4^+-N entering N/D on day d (g)

$Y_{N_2O,N,d}$ = Mass N_2O produced per gram NH_4^+-N entering N/D on day d (g)

$Y_{NH_3,N,d}$ = Mass NH_3 produced per gram NH_4^+-N entering N/D on day d (g)

$C_{NH_4^+-N,LE,d}$ = Concentration NH_4^+-N in lagoon liquid effluent on day d (mg/L)

These gas consumption and production rates are shown in Table K3 with low, mean, and high design values. Low and high design values are consumption and production rates one standard deviation below and above the mean rates, respectively.

Table K3 - Gas consumption (O_2) and production (CO_2, CH_4, N_2O, NH_3) rates in the N tank (g/g NH_4^+-N).

	CO_2	CH_4	N_2O	NH_3	O_2
Average	4.9	0.0013	0.10	0.0026	3.8
Std. Dev.	1.5	0.0026	0.03	0.0024	0.37
Low	3.4	0.0005	0.067	0.0002	3.4
Mean	4.9	0.0013	0.097	0.0026	3.8
High	6.4	0.0038	0.13	0.0049	4.1

To determine the mass of gas produced and consumed in the full scale N tank, the values in Table K3 were multiplied by the full scale mass flow of NH_4^+-N into the N tank: 13,614 kg NH_4^+-N/yr. Table K4 displays anticipated gas production and consumption of the full scale system.

Table K4 - Expected full scale gas consumption and production in the N tank (metric tons/year)

	CO_2	CH_4	N_2O	NH_3	O_2
Low	47	0.0068	0.91	0.0028	46
Mean	67	0.017	1.3	0.035	51
High	88	0.052	1.7	0.067	56

APPENDIX L – METHOD TO CALCULATE GAS PRODUCTION IN THE DENITRIFICATION TANK

The theoretical quantity of gas produced by the denitrification tank assumes that all inorganic nitrogen removed in the N/D system is converted to NH_3, N_2O or N_2 and released from the D tank. The quantity of inorganic nitrogen removed in the N/D system is the seven-day running average of the difference between the TN in the lagoon effluent and the TN in the N tank effluent:

$$C_{TN-N,lost,d} = C_{TN-N,LE,d} - C_{TN-N,N,d}$$

$$M_{TN-N,lost,d} = C_{TN-N,lost,d} \times Q_{MCD1,d} \times \frac{1\ g}{1000\ mg}$$

$$n_{N,lost,d} = M_{TN-N,lost,d} \times \frac{1\ mol\ N}{14.01\ g\ N}$$

Where:

$C_{TN-N,lost,d}$ = Concentration of TN lost in the N/D system on day d (mg/L)

$C_{TN-N,LE,d}$ = Concentration of TN in the lagoon effluent on day d, TN_{in} (mg/L)

$C_{TN-N,N,d}$ = Concentration of TN in the N tank effluent on day d, TN_{out} (mg/L)

$M_{TN-N,lost,d}$ = Mass TN lost in the N/D system on day d (g)

$n_{TN-N,lost,d}$ = Mols nitrogen lost in the N/D system on day d (mols)

This assumes that the flow rates into and out of the system are equal (MCD1 = MCD4). The amount of NH_3, N_2O, CO_2, and CH_4 in the D tank headspace was periodically measured using gas chromatography. N_2O, CO_2 and CH_4 were measured as percent by volume and NH_3 was measured in parts per million, but displayed as percent by volume (Table L1).

Table L1 - Measured quantities of gases in pilot scale D tank headspace (percent by volume).

Date	CO_2	CH_4	N_2O	NH_3
11/26/10	29.4	1.4	2.53	
12/10/10	27.8	0.7	0.31	
01/19/11	26.1	2.8	0.16	
01/26/11	14.1	2.5	0.10	
02/09/11	12.3	1.8	0.06	
02/17/11	12.2	1.7	0.09	
02/23/11	9.4	1.7	0.67	
03/02/11	5.7	1.5	0.36	
03/08/11	5.2	1.5	0.32	0.0059
03/23/11	7.7	1.8	0.01	0.0082
03/29/11	6.7	1.8	0.01	0.0030
04/05/11	8.9	2.3	0.01	0.0031
04/13/11	7.7	2.3	0.01	0.0032
04/19/11	9.1	2.1	0.01	0.0017
04/27/11	9.9	2.9	0.01	0.0039
05/04/11	7.6	4.1	0.01	0.0037
05/10/11	10.2	2.7	0.17	0.0037
05/18/11	15.1	3.2	0.18	0.0002

All remaining gas in the D tank headspace is assumed to be N2, consistent with the expected reaction in the D tank: Organic Matter + NO_3^- → CO_2 + H_2O + N_2 + OH^-.

$$X_{N_2,D,d} = 100 - X_{CO_2,D,d} + X_{CH_4,D,d} + X_{N_2O,D,d} + X_{NH_3,D,d}$$

Where:

$X_{N_2,D,d}$ = Percent N_2 in D tank off-gas on day d

$X_{CO_2,D,d}$ = Percent CO_2 in D tank off-gas on day d

$X_{CH_4,D,d}$ = Percent CH_4 in D tank off-gas on day d

$X_{N_2O,D,d}$ = Percent N_2O in D tank off-gas on day d

$X_{NH_3,D,d}$ = Percent NH_3 in D tank off-gas on day d

The relative ratios of each of the nitrogen-containing mass species on day d were calculated. On days where the NH_3 was not measured, it was assumed that no NH_3 was produced.

$$r_{NH_3,D,d} = \frac{X_{NH_3,D,d}}{X_{NH_3,D,d} + X_{N_2O,D,d} + X_{N_2,D,d}}$$

$$r_{N_2O,D,d} = \frac{X_{N_2O,D,d}}{X_{NH_3,D,d} + X_{N_2O,D,d} + X_{N_2,D,d}}$$

$$r_{N_2,D,d} = \frac{X_{N_2,D,d}}{X_{NH_3,D,d} + X_{N_2O,D,d} + X_{N_2,D,d}}$$

Where:

$r_{NH_3,D,d}$ = Ratio of NH_3 in D tank off-gas on day d

$r_{N_2O,D,d}$ = Ratio of N_2O in D tank off-gas on day d

$r_{N_2,D,d}$ = Ratio of N_2 in D tank off-gas on day d

The moles of each gas produced were calculated by multiplying these relative ratios by the moles of TN lost on the corresponding day. For N_2 and N_2O this value was then divided by two because each mole of N_2 and N_2O contains two moles of nitrogen.

$$n_{NH_3,D,d} = r_{NH_3,D,d} \times n_{N,lost,d}$$

$$n_{N_2O,D,d} = r_{N_2O,D,d} \times n_{N,lost,d} \times \frac{1\ mol\ N_2O}{2\ mol\ N}$$

$$n_{N_2,D,d} = r_{N_2,D,d} \times n_{N,lost,d} \times \frac{1\ mol\ N_2}{2\ mol\ N}$$

Where:

$n_{NH_3,D,d}$ = Mols NH_3 produced in D tank on day d

$n_{N_2O,D,d}$ = Mols N_2O produced in D tank on day d

$n_{N_2,D,d}$ = Mold N_2 produced in D tank on day d

The produced volume of each nitrogen-containing gas species on day d is calculated using the ideal gas law and the trailer temperature on the corresponding day.

$$V = \frac{n \times R \times (T_{t,d} + 273.15)}{P}$$

Where:

V = Volume of gas produced on day d (L)

n = Moles of gas produced on day d

P = Atmospheric pressure (assumed 1 atm)

R = Ideal gas constant (assume 0.0821L atm K^{-1} mol^{-1})

$T_{t,d}$ = Temperature in trailer on day d (degrees C)

These calculated volumes are used to calculate the total volume of gas produced and thus the volume of CO_2 and CH_4 produced. The volumes of CO_2 and CH_4 produced are converted to moles using the ideal gas law and the corresponding trailer temperature. All molar measurements of gas production are converted to masses using each species' molecular weight.

$$V_{G,D,d} = \frac{V_{N_2O,D,d}}{\left(\frac{X_{N_2O,D,d}}{100}\right)}$$

$$V_{CO_2,D,d} = V_{G,D,d} \times X_{CO_2,D,d}$$

$$V_{CH_4,D,d} = V_{G,D,d} \times X_{CH_4,D,d}$$

$$M_{CO_2,D,d} = \frac{P \times V_{CO_2,D,d}}{R \times T_{t,d}} \times \frac{44.0098\ g\ CO_2}{mol\ CO_2}$$

$$M_{CH_4,D,d} = \frac{P \times V_{CH_4,D,d}}{R \times T_{t,d}} \times \frac{16.04276\ g\ CH_4}{mol\ CH_4}$$

$$M_{N_2O,D,d} = n_{N_2O,D,d} \times \frac{44.01288\ g\ N_2O}{mol\ N_2O}$$

$$M_{NH_3,D,d} = n_{NH_3,D,d} \times \frac{17.031\ g\ NH_3}{mol\ NH_3}$$

$$M_{N_2,D,d} = n_{N_2,D,d} \times \frac{28.02\ g\ N_2}{mol\ N_2}$$

Where:

$V_{N_2O,D,d}$ = Volume N_2O produced in D tank on day d (L)

$V_{G,D,d}$ = Volume off-gas produced in D tank on day d (L)

$V_{CO_2,D,d}$ = Volume CO_2 produced in D tank on day d (L)

$V_{CH_4,D,d}$ = Volume CH_4 produced in D tank on day d (L)

$M_{CO_2,D,d}$ = Mass CO_2 produced on D tank on day d (g)

$M_{CH_4,D,d}$ = Mass CH_4 produced in D tank on day d (g)

$M_{N_2O,D,d}$ = Mass N_2O produced in D tank on day d (g)

$M_{NH_3,D,d}$ = Mass NH_3 produced in D tank on day d (g)

$M_{N_2,D,d}$ = Mass N_2 produced in D tank on day d (g)

The mass of each species produced was divided by the mass of TN entering the N/D system on the corresponding day d to give the mass (g) of each species produced per mass (g) of nitrogen entering the system. This was also done to calculate the mass of each gas species produced per mass of NH_4^+-N entering the system as all inorganic nitrogen entering the N/D system is assumed to be in the form of ammonium. The two values were nearly equal. The mean gas production rates were calculated from the available data and low, mean, and high production rates were chosen (Table L2).

Table L2 - Mass production of D tank off-gases per mass NH_4^+-N entering N/D system (g/g).

	NH_3	N_2	N_2O	CO_2	CH_4
Average	0.000028	0.75	0.0023	0.16	0.0095
Std. Dev	0.000014	0.14	0.0026	0.10	0.0035
Low	0.000013	0.62	0.0002	0.06	0.0060
Mean	**0.000028**	**0.75**	**0.0023**	**0.16**	**0.0095**
High	0.000042	0.89	0.0049	0.26	0.0129

The anticipated mass of each gas produced by the full scale D tank is calculated by multiplying the above gas production rates by the full scale design flow rate, 15,940 L/day, and the expected lagoon concentration 2,340 mg NH_4^+-N/L. Expected annual gas production is shown in Table L3.

Table L3 - Mass of D tank off-gases produced annually (metric tons).

	NH_3	N_2	N_2O	CO_2	CH_4
Low	0.00018	8.4	0.0020	0.83	0.082
Mean	0.00038	10.3	0.031	2.2	0.13
High	0.00057	12.1	0.067	3.6	0.18

APPENDIX M – CALCULATIONS OF GREENHOUSE GAS CREDITS

The reduction in greenhouse gas production was calculated using the United Nations Framework Convention on Climate Change's Clean Development Mechanism method AMS iii D *(76)*. This method of calculating reduction in greenhouse gas emissions is designed for methane recovery in animal manure management systems. The method compares the emissions of a baseline scenario with those of the project scenario in (metric) tons of CO_2 equivalents (tCO_2e). The baseline emissions are calculated as follows:

$$BE_y = GWP_{CH4} * D_{CH4} * UF_b * \sum_{j,LT} MCF_j * B_{0,LT} * N_{LT,y} * VS_{LT,y} * MS\%_{Bl,j}$$

Where:

BE_y = Baseline emissions in year y (tCO_2e)

GWP_{CH4} = Global Warming Potential (GWP) of CH_4 (21)

D_{CH4} = CH_4 density (0.00067 t/m^3 at room temperature (20°C) and 1 atm pressure)

UF_b = Model correction factor to account for model uncertainties (0.94)

LT = Index for all types of livestock

j = Index for all manure management systems

MCF_j = Annual methane conversion factor (MCF) for the baseline animal manure management system j

$B_{0,LT}$ = Maximum methane producing potential of the volatile solid generated for animal type LT (m^3 CH_4/kg dm)

$N_{LT,y}$ = Annual average number of animals of type LT in year y

$VS_{LT,y}$ = Volatile solids for livestock LT entering the animal manure management system in year y (on a dry weight basis, kg dw/animal/year)

$MS\%_{Bl,j}$ = Fraction of manure handled in baseline animal manure management system j

The only livestock type and manure management system at Butler Farms are hogs and lagoons, respectively ($MS\%_{Bl,j} = 100\%$). Table 10A-7 of 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Chapter 10 *(97)* is used to determine continent-specific values for $B_{0,LT}$, $VS_{LT,y}$, and MCF_j for market swine. B_0 is 0.48 m^3 CH_4/kg VS, VS_y is 0.27 kg/hd/day, and MCF is 74% (assuming an annual temperature of 15°C *(98)*. These values give a baseline emissions value of:

$$BE_y = 1014.7\ tCO_2e/yr$$

Project activity emissions are calculated as follows:

$$PE_y = PE_{PL,y} + PE_{flare,y} + PE_{power,y} + PE_{transp,y} + PE_{storage,y} + PE_{N/D,y}$$

Where:

PE_y = Project emissions in year y (tCO_2e)

$PE_{PL,y}$ = Emissions due to physical leakage of biogas in year y (tCO_2e)

$PE_{flare,y}$ = Emissions from flaring or combustion of the biogas stream in the year y (tCO_2e)

$PE_{power,y}$ = Emissions from the use of fossil fuel or electricity for the operation of the installed facilities in the year y (tCO_2e)

$PE_{transp,y}$ = Emissions from incremental transportation in the year y (tCO_2e)

$PE_{storage,y}$ = Emissions from the storage of manure (tCO_2e)

$PE_{N/D,y}$ = Emissions from the off-gas of the N/D system (tCO_2e), not included in

original UN methodology

Emissions due to physical leakage associated with the project can be calculated:

$$PE_{PL,y} = 0.10 * GWP_{CH4} * D_{CH4} * \sum_{i,LT} B_{0,LT} * N_{LT,y} * VS_{LT,y} * MS\%_{i,y}$$

Where:

i = Index for all treatment systems

$MS\%_{i,y}$ = Fraction of manure handled in system i in year y (100%)

$$PE_{PL,y} = 145.9\ tCO_2e/yr$$

$PE_{flare,y}$ is assumed to be zero because all biogas produced will be routed to the generator instead of being flared. $PE_{transp,y}$ is assumed to be zero because the manure is not transported off-site for treatment. $PE_{storage,y}$ is also assumed to be zero because the waste is not stored prior to entering the anaerobic digester. Losses that occur in the barn pits are assumed negligible.

$PE_{power,y}$ is calculated in accordance with UNFCCC-CDM AMD-1.D for grid connected renewable electricity generation *(99)* and represents emissions from fossil fuel power production for the additional power needed to operate the project.

$$PE_{power,y} = \left(EG_{PJ,retrofit,y} - EG_{BL,retrofit,y}\right) \times EF_{CO_2,grid,y}$$

Where:

$EG_{PJ,retrofit,y}$ = Net electricity supplied to the project by the grid in year y (MWh)

$EG_{BL,retrofit,y}$ = Electricity that would have been supplied by the grid in the absence of the project activity in year y (MWh)

$EF_{CO_2,grid,y}$ = CO_2 emissions factor of the grid in year y (t CO_2/MWh)

The methane capture system is assumed to generate 102.7 MWh of power a year, with 176.0 MWh demanded by the farm before the project, and 364.9 MWh demanded by the farm after the project. The emissions factor was assumed to be that of the average North Carolina grid, 0.728 t CO_2/MWh *(100)*. This value accounts for CO_2, CH_4 and N_2O emissions from energy production.

$$PE_{power,y} = 62.8\ tCO_2e/yr$$

$PE_{N/D,y}$ is equal to the greenhouse gases in the N and D tank off-gas as calculated in Appendices K and L. Table M1 displays the mass of gas expected to be produced annually (in tCO_2e) in each tank assuming a flow rate of 15,940 L/day and a NH_4^+-N concentration of 2,340 mg/L. CO_2 equivalents were calculated using the 100-year GWP of carbon dioxide (1), methane (21) and nitrous oxide (310) as identified in the 1996 the Second Assessment Report by the Intergovernmental Panel of Climate Change (IPCC) *(101)*. Due to its high GWP, N_2O was found to be the dominant contributor to GHG emissions.

Table M1 - Estimated full scale GHG production (metric tons/year). Assumes Qin=15,940 L/year, lagoon NH_4^+-N concentration of 2,340 mg/L, CO_2 GWP = 1, CH_4 GWP = 21, N_2O GWP = 310.

		GHG Production (tons/year)			GHG Production (tons CO_2e/year)			
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	Total
N Tank	Low	47	0.0068	0.91	47	0.14	283	330
	Mean	67	0.017	1.3	67	0.36	409	476
	High	88	0.052	1.7	88	1.1	534	622
D Tank	Low	0.83	0.082	0.0020	0.83	1.7	0.0020	2.6
	Mean	2.2	0.13	0.031	2.2	2.7	9.6	15
	High	3.6	0.18	0.067	3.6	3.7	21	28
Total (Mean)		69	0.15	1.3	69	3.1	418	**490**

Project emissions are as follows:

$$PE_y = 145.9 + 0 + 62.8 + 0 + 0 + 490 = 698.7\ tCO_2e/yr$$

To be conservative, the emissions reductions are the smaller of two values: the difference between baseline emissions and project emissions as measured above, and the difference between methane captured and the emissions required for the operation of the project.

$$ER_y = min\left[\left(BE_y - PE_y\right), \left(MD_y - PE_{power,y,}\right)\right]$$

Where:

ER_y = Emission reductions achieved by the project activity based on monitored values for year y (tCO_2e)

MD_y = Methane captured and destroyed or used gainfully by the project activity in year y (tCO_2e)

$$BE_y - PE_y = 1014.7 - 698.7 = 316\ tCO_2e/yr$$

$$MD_y - PE_{power,y,} = 1071.1 - 62.8 = 1008\ tCO_2e/yr$$

$$ER_y = 316\ tCO_2e/yr$$

Appendix N – Definitions of Abbreviations and Terms

$B_{0,LT}$ = Maximum methane producing potential of the volatile solid generated for animal type LT (m^3 CH_4/kg dm)

BE_y = Baseline emissions in year y (tCO_2e)

$C_{NH_4^+-N,LE,d}$ = Concentration NH_4^+-N in lagoon liquid effluent on day d (mg/L)

$C_{NH_4^+-N,L}$ = Concentration of NH_4^+-N in the lagoon (mg/L)

$C_{NO_2^--N,N,d}$ = Concentration of NO_2-N in the nitrification tank effluent on day d (mg/L)

$C_{NO_3^--N,N,d}$ = Concentration of NO_3-N in the nitrification tank effluent on day d (mg/L)

$C_{TN-N,LE,d}$ = Concentration of TN in the lagoon effluent on day d, TN_{in} (mg/L)

$C_{TN-N,N,d}$ = Concentration of TN in the N tank effluent on day d, TN_{out} (mg/L)

$C_{TN-N,lost,d}$ = Concentration of TN lost in the N/D system on day d (mg/L)

$C_{x,L,d}$ = Concentration of species x in lagoon on day d

$C_{x,N,d}$ = Concentration of species x in N tank on day d

D_{CH4} = CH_4 density (0.00067 t/m^3 at room temperature (20°C) and 1 atm pressure)

$EF_{CO_2,grid,y}$ = CO_2 emissions factor of the grid in year y (t CO_2/MWh)

$EG_{BL,retrofit,y}$ = Electricity that would have been supplied by the grid in the absence of the project activity in year y (MWh)

$EG_{PJ,retrofit,y}$ = Net electricity supplied to the project by the grid in year y (MWh)

ER_y = Emission reductions achieved by the project activity based on monitored values for year y (tCO_2e)

GWP_{CH4} = Global Warming Potential (GWP) of CH_4 (21)

HRT_D = Hydraulic retention time of the D tank

HRT_N = Hydraulic retention time of the N tank

HRT_T = Combined hydraulic retention time of N and D tank

i = Index for all treatment systems

j = Index for all manure management systems

LT = Index for all types of livestock

$M_{CH_4,D,d}$ = Mass CH_4 produced in D tank on day d (g)

$M_{CH_4,N,d}$ = Mass of CH_4 in N tank off-gas on day d (g)

$M_{CO_2,D,d}$ = Mass CO_2 produced on D tank on day d (g)

$M_{CO_2,N,d}$ = Mass of CO_2 in N tank off-gas on day d (g)

$M_{N_2,D,d}$ = Mass N_2 produced in D tank on day d (g)

$M_{N_2O,D,d}$ = Mass N_2O produced in D tank on day d (g)

$M_{N_2O,N,d}$ = Mass of N_2O in N tank off-gas on day d (g)

$M_{NH_3,D,d}$ = Mass NH_3 produced in D tank on day d (g)

$M_{NH_3,N,d}$ = Mass of NH_3 in N tank off-gas on day d (g)

$M_{NH_4^+-N,in,d}$ = Mass of NH_4^+-N entering the lagoon on day d (mg)

$M_{NH_4^+-N,in,y}$ = Mass of NH_4^+-N entering the lagoon in year y (mg)

$M_{O_2,NO_2^-,d}$ = Mass of O_2 consumed during ammonia oxidation on day d (g)

$M_{O_2,NO_3^-,d}$ = Mass of O_2 consumed during nitrite oxidation on day d (g)

$M_{O_2,in,d}$ = Mass of oxygen pumped into nitrification tank in day d (g)

MCF_j = Annual methane conversion factor (MCF) for the baseline animal manure management system j

MD_y = Methane captured and destroyed or used gainfully by the project activity in year y (tCO_2e)

$MS\%_{Bl,j}$ = Fraction of manure handled in baseline animal manure management system j

$MS\%_{i,y}$ = Fraction of manure handled in system i in year y (100%)

$M_{TN-N,lost,d}$ = Mass TN lost in the N/D system on day d (g)

$M_{x,A,d}$ = Mass of species x entering storage from the nitrification/denitrification system (N tank) on day d

$M_{x,B,d}$ = Mass of species x entering lagoon from barn waste collection pits on day d

$M_{x,G,d}$ = Mass of species x exiting nitrification/denitrification system in gaseous form on day d

$M_{x,L,d}$ = Mass of species x in lagoon on day d

$M_{x,LE,d}$ = Mass of species x entering nitrification/denitrification system (D tank) from lagoon on day d

$M_{x,P,d}$ = Mass of species x entering barn waste collection pits from lagoon on day d

$M_{x,R,d}$ = Mass of species x entering lagoon from the nitrification/denitrification system (N tank) on day d

$M_{x,S,d}$ = Mass of species x applied to spray field on day d

$M_{x,in}$ = Mass of species x entering system from hog waste

$n_{N_2,D,d}$ = Mold N_2 produced in D tank on day d

$n_{N_2O,D,d}$ = Moles N_2O produced in D tank on day d

$n_{NH_3,D,d}$ = Moles NH_3 produced in D tank on day d

$n_{TN-N,lost,d}$ = Moles nitrogen lost in the N/D system on day d (moles)

$N_{LT,y}$ = Annual average number of animals of type LT in year y

$PE_{N/D,y}$ = Emissions from the off-gas of the N/D system (tCO_2e), not included in original UN methodology

$PE_{PL,y}$ = Emissions due to physical leakage of biogas in year y (tCO_2e)

$PE_{flare,y}$ = Emissions from flaring or combustion of the biogas stream in the year y (tCO_2e)

$PE_{power,y}$ = Emissions from the use of fossil fuel or electricity for the operation of the installed facilities in the year y (tCO_2e)

$PE_{storage,y}$ = Emissions from the storage of manure (tCO_2e)

$PE_{transp,y}$ = Emissions from incremental transportation in the year y (tCO_2e)

PE_y = Project emissions in year y (tCO_2e)

Q_A = Flow rate of liquid from the nitrification/denitrification system (N tank) to storage

Q_B = Flow rate of liquid flushed from barn waste collection pits to lagoon

$Q_{LE,d}$ = Daily flow rate of lagoon effluent to the N/D system (L/d)

Q_{LE} = Flow rate of liquid from lagoon into nitrification/denitrification system (D tank)

$Q_{O_2,in,d}$ = Oxygen flow rate into nitrification tank on day d (L/min)

Q_P = Flow rate of liquid from the lagoon to the barn waste collection pits

Q_R = Flow rate of liquid from the nitrification/denitrification system (N tank) to lagoon

Q_S = Flow rate of liquid from the lagoon to spray fields

$Q_{in,y}$ = Liquid production from barns in year y (L/year)

Q_{in} = liquid flow rate into system from hog waste, spilled drinking water, sprinkler water and barn-washing water

$r_{N_2,D,d}$ = Ratio of N_2 in D tank off-gas on day d

$r_{N_2O,D,d}$ = Ratio of N_2O in D tank off-gas on day d

$r_{NH_3,D,d}$ = Ratio of NH_3 in D tank off-gas on day d

$T_{t,d}$ = Temperature in trailer on day d (degrees C)

UF_b = Model correction factor to account for model uncertainties (0.94)

$V_{CH_4,D,d}$ = Volume CH_4 produced in D tank on day d (L)

$V_{CH_4,N,d}$ = Volume of CH_4 in N tank off-gas on day d (L)

$V_{CO_2,D,d}$ = Volume CO_2 produced in D tank on day d (L)

$V_{CO_2,N,d}$ = Volume of CO_2 in N tank off-gas on day d (L)

$V_{G,D,d}$ = Volume off-gas produced in D tank on day d (L)

V_L = volume of lagoon

$V_{N_2O,D,d}$ = Volume N_2O produced in D tank on day d (L)

$V_{N_2O,N,d}$ = Volume of N_2O in N tank off-gas on day d (L)

$V_{NH_3,N,d}$ = Volume of NH_3 in N tank off-gas on day d (L)

$V_{O_2,N,d}$ = Volume of O_2 in N tank off-gas on day d (L)

V_T = combined liquid volume of N and D tanks

$VS_{LT,y}$ = Volatile solids for livestock LT entering the animal manure management system in year y (on a dry weight basis, kg dw/animal/year)

$X_{CH_4,D,d}$ = Percent CH_4 in D tank off-gas on day d

$X_{CH_4,N,d}$ = Percent CH_4 in N tank off-gas on day d

$X_{CO_2,D,d}$ = Percent CO_2 in D tank off-gas on day d

$X_{CO_2,N,d}$ = Percent CO_2 in N tank off-gas on day d

$X_{N_2,D,d}$ = Percent N_2 in D tank off-gas on day d

$X_{N_2O,D,d}$ = Percent N_2O in D tank off-gas on day d

$X_{N_2O,N,d}$ = Percent N_2O in N tank off-gas on day d

$X_{NH_3,D,d}$ = Percent NH_3 in D tank off-gas on day d

$X_{NH_3,N,d}$ = Percent NH_3 in N tank off-gas on day d

$X_{O_2,N,d}$ = Percent O_2 in N tank off-gas on day d

$Y_{CH_4,N,d}$ = Mass CH_4 produced per gram NH_4^+-N entering N/D on day d (g)

$Y_{CO_2,N,d}$ = Mass CO_2 produced per gram NH_4^+-N entering N/D on day d (g)

$Y_{N_2O,N,d}$ = Mass N_2O produced per gram NH_4^+-N entering N/D on day d (g)

$Y_{NH_3,N,d}$ = Mass NH_3 produced per gram NH_4^+-N entering N/D on day d (g)

$Y_{O_2,N,d}$ = Mass O_2 consumed per gram NH_4^+-N entering N/D on day d (g)

APPENDIX O – PILOT SCALE RAW DATA

Table O1 – Average measured NH_4^+-N in pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Lagoon Effluent		N Tank		D Tank	
		mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev
9/10/10	1			87.0	3.8	164.1	15.2
9/11/10	2			91.6	7.5	350.2	5.1
9/13/10	4			137.4	2.0	551.5	39.0
9/14/10	5	2,663.1	610.6	104.1	6.9	558.7	17.1
9/16/10	7	2,513.6	65.6	59.1	32.0	550.5	23.3
9/18/10	9	2,435.4	98.5	79.8	3.3	323.5	13.4
9/19/10	10	2,318.3	61.3	77.0	3.5	276.7	17.7
9/23/10	14	2,447.0	43.5	35.2	1.5	226.0	11.7
9/26/10	17	2,439.9	138.7	97.1	1.2	262.0	24.6
9/27/10	18	2,305.9	55.6	103.9	1.3	168.2	47.9
9/29/10	20			87.8	2.4	110.6	13.9
10/1/10	22	2,391.6	66.2	56.4	5.9	88.5	7.7
10/4/10	25	2,153.0	35.2	108.9	0.9	690.5	18.6
10/6/10	27	2,263.3	101.7	162.3	2.4	664.6	15.8
10/8/10	29	2,242.3	156.8	228.9	3.8	711.3	23.7
10/11/10	32	2,170.7	89.2	351.6	8.9	549.8	180.3
10/13/10	34	2,323.8	63.3	386.0	4.8	694.5	9.4
10/15/10	36	2,168.8	18.5	329.5	3.3	693.7	11.8
10/18/10	39	2,217.3	242.4	432.9	14.7	790.8	7.1
10/22/10	43	2,053.5	69.2	349.8	4.2	708.3	16.6
10/25/10	46	1,764.7	38.0	286.6	5.9	739.7	55.1
10/27/10	48	2,493.1	73.5	265.5	18.4	854.0	4.4
10/29/10	50	2,343.2	125.3	56.4	1.8	739.7	15.5
11/1/10	53	2,023.4	53.4	106.9	7.6	606.1	11.1
11/3/10	55	1,843.9	609.8	95.0	28.4	614.0	6.0
11/5/10	57	1,945.2	32.8	158.6	4.9	574.9	14.4
11/8/10	60	2,225.3	135.4	321.8	6.7	688.0	16.5
11/10/10	62	2,466.0	293.2	306.7	127.2	742.1	24.4
11/12/10	64	2,233.1	208.7	384.0	16.0	719.8	21.1
11/15/10	67	2,341.7	120.3	341.2	13.6	682.9	3.8
11/17/10	69	2,246.0	138.4	279.3	9.8	661.9	19.4
11/19/10	71	2,601.0	94.0	216.3	4.4	700.5	29.0
11/22/10	74	2,584.5	161.9	83.8	1.7	662.6	18.5
11/24/10	76	2,346.3	71.3	45.3	2.4	575.3	33.7
11/29/10	81	2,267.5	97.2	73.0	1.4	538.5	6.1
12/1/10	83	2,361.3	86.5	54.8	1.4	532.3	10.2
12/3/10	85	2,370.3	52.6	67.2	5.8	537.8	8.6
12/6/10	88	2,364.2	116.5	77.6	1.7	564.5	9.3
12/10/10	92	2,306.6	41.6	68.1	22.3	1,391.8	48.5
12/13/10	95	2,505.7	116.6	90.2	1.9	1,903.8	36.3
12/15/10	97	2,403.1	23.6	52.6	2.1	2,376.7	59.4
12/17/10	99	2,321.2	78.8	20.2	3.9	1,602.2	127.5

Table O1 (cont.) – Average measured NH_4^+-N in pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Lagoon Effluent		N Tank		D Tank	
		mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev
12/20/10	102	2,405.3	118.9	119.1	3.4	1,040.1	13.7
12/23/10	105	2,306.5	128.2	127.6	3.8	822.4	12.7
12/25/10	107	2,193.5	29.6	85.2	1.8	726.8	62.3
12/28/10	110	2,140.0	70.4	136.0	2.7	667.8	23.2
12/31/10	113	2,219.5	65.0	233.0	3.4	678.6	12.8
1/3/11	116	2,299.3	62.7	224.1	47.5	665.2	17.1
1/5/11	118	2,311.5	112.1	268.2	6.0	772.8	3.2
1/7/11	120	2,463.8	75.5	277.2	1.9	792.5	50.7
1/10/11	123	2,588.6	146.0	311.0	9.1	845.4	23.3
1/12/11	125	2,436.4	94.1	332.4	8.5	853.4	33.5
1/14/11	127	2,235.2	35.7	405.8	7.3	840.4	9.4
1/17/11	130	2,238.9	117.0	691.7	5.7	889.4	8.7
1/18/11	131	2,147.3	37.5	410.8	15.7	731.1	287.3
1/21/11	134	2,269.0	116.9	471.1	12.2	949.9	25.7
1/24/11	137	2,431.1	177.5	537.6	11.2	1,096.4	43.8
1/26/11	139	2,134.2	28.3	598.7	11.1	1,090.3	15.0
1/28/11	141	2,476.5	153.4	486.6	1.5	982.6	30.8
1/31/11	144	2,436.8	34.3	293.9	14.1	980.2	23.7
2/2/11	146	2,255.0	110.1	195.6	16.6	847.0	32.8
2/4/11	148	2,506.8	42.9	119.3	57.0	735.9	13.7
2/11/11	155	2,472.7	69.7	170.5	5.7	810.6	11.8
2/14/11	158	2,333.0	107.9	199.1	1.7	804.7	17.3
2/17/11	161	2,333.5	57.6	172.4	7.0	737.7	25.2
2/18/11	162	2,249.9	54.2	168.0	7.5	802.0	11.3
2/21/11	165	2,518.6	98.4	124.4	0.6	857.7	15.7
2/23/11	167	2,460.3	85.2	84.0	0.7	707.1	29.3
2/25/11	169	2,561.6	96.3	111.2	1.1	676.7	6.5
2/28/11	172	2,665.9	36.9	157.3	2.5	713.4	11.9
3/3/11	175	2,306.9	101.4	103.7	1.7	755.5	5.3
3/5/11	177	2,375.0	66.0	130.4	1.1	727.7	25.9
3/7/11	179	2,489.8	62.7	159.6	4.7	701.2	16.4
3/9/11	181	2,253.9	24.1	153.3	5.2	718.8	29.2
3/11/11	183	2,457.4	115.1	120.2	12.9	662.0	14.6
3/14/11	186	2,536.3	129.1	91.6	2.9	684.2	13.0
3/16/11	188	2,104.0	133.6	85.7	0.8	592.3	25.3
3/21/11	193	2,294.7	82.8	68.2	3.8	624.9	9.7
3/25/11	197	2,470.4	68.0	61.2	2.9	606.0	18.4
3/30/11	202	2,306.2	45.7	92.2	3.9	687.0	62.8
4/1/11	204			110.6	2.0		
4/4/11	207			95.2	2.5	652.3	6.8
4/6/11	209	2,625.1	53.4	63.5	2.6	672.4	7.7
4/8/11	211	2,468.9	40.3	68.7	3.4	673.7	3.4
4/11/11	214	2,363.8	60.7	66.6	1.7	654.5	1.1
4/13/11	216	2,348.8	93.6	58.0	2.5	626.0	12.5

Table O1 (cont.) – Average measured NH_4^+-N in pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Lagoon Effluent		N Tank		D Tank	
		mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev
4/15/11	218	2,318.4	41.8	60.9	0.8	570.0	11.7
4/18/11	221	2,329.5	42.4	57.9	0.2	572.6	7.3
4/20/11	223	2,218.1	31.0	41.2	1.7	516.0	24.4
4/25/11	228	2,386.4	103.7	27.3	0.7	501.7	5.6
4/27/11	230	2,375.0	27.8	28.3	1.9	529.8	3.8
4/29/11	232	2,431.1	64.8	30.5	1.4	566.1	4.3
5/2/11	235	2,331.3	64.8	52.2	2.0	583.9	9.7
5/4/11	237			42.1	1.2	540.7	9.2
5/6/11	239	2,466.9	119.0	29.2	0.3	498.9	5.6
5/9/11	242	2,159.6	39.0	26.1	0.4	552.1	45.6
5/11/11	244	2,446.0	114.7	16.3	0.8	601.7	7.4
5/13/11	246	2,394.6	101.3	38.3	0.5	653.7	13.1
5/18/11	251	2,325.7	75.8	7.6	0.6	573.7	4.4
AVERAGE		**2,338.4**		**164.8**		**699.6**	
Std. Dev.		**161.5**		**141.4**		**307.4**	

Table O2 - Average measured NO_2^--N in pilot scale N tank and D tank.

Date	Day	N Tank		D Tank	
		mg-N/L	Std Dev	mg-N/L	Std Dev
9/10/10	1	611.25	14.20	599.30	55.86
9/11/10	2	643.15	4.03	548.30	12.11
9/13/10	4	603.95	4.67	454.85	15.70
9/14/10	5	595.45	28.36	423.75	3.48
9/16/10	7	642.30	38.44	399.95	7.31
9/18/10	9	645.50	40.80	481.50	21.21
9/19/10	10	663.25	14.73	477.50	17.87
9/23/10	14	651.38	32.68	547.63	16.33
9/26/10	17	603.31	3.99	534.69	11.32
9/27/10	18	609.75	18.02	505.69	9.86
9/29/10	20	585.06	10.81	633.94	10.28
10/1/10	22	604.50	26.64	598.94	27.10
10/4/10	25	596.25	9.49	484.13	50.42
10/6/10	27	608.00	24.14	424.06	5.54
10/8/10	29	582.44	27.44	416.81	12.35
10/11/10	32	589.00	6.74	436.63	19.06
10/13/10	34	607.00	5.66	402.63	20.15
10/15/10	36	723.00	21.32	390.88	34.56
10/18/10	39	615.56	15.81	377.44	46.04
10/22/10	43	604.88	6.69	381.56	6.10
10/25/10	46	514.50	7.67	335.75	20.40
10/27/10	48	485.88	20.18	284.44	1.20
10/29/10	50	372.00	3.85	266.63	5.72

Table O2 (Cont.) - Average measured NO_2^--N in pilot scale N tank and D tank.

Date	Day	N Tank		D Tank	
		mg-N/L	Std Dev	mg-N/L	Std Dev
11/1/10	53	-6.38	2.29	140.44	4.67
11/3/10	55	-15.38	0.48	43.19	0.52
11/5/10	57	-3.25	0.29	-1.38	0.14
11/8/10	60	28.59	0.21	0.63	0.07
11/10/10	62	41.18	0.39	1.94	0.24
11/12/10	64	48.07	0.79	1.54	0.40
11/15/10	67	61.44	2.54	-1.50	0.41
11/17/10	69	142.13	0.75	20.81	1.92
11/19/10	71	283.65	3.12	65.29	1.74
11/22/10	74	292.18	10.61	107.54	7.86
11/24/10	76	191.83	8.20	107.90	6.50
11/29/10	81	2.86	0.15	3.59	0.36
12/1/10	83	3.13	0.04	-0.73	0.13
12/3/10	85	6.05	0.13	0.03	0.05
12/6/10	88	15.13	0.14	-0.73	0.06
12/10/10	92	11.58	0.09	1.07	0.04
12/13/10	95	23.10	0.36	2.49	0.05
12/15/10	97	16.53	0.16	0.68	0.01
12/17/10	99	5.32	0.66	0.33	0.17
12/20/10	102	97.18	4.49	11.42	0.04
12/23/10	105	200.60	2.79	40.56	0.86
12/25/10	107	120.25	12.08	61.70	2.74
12/28/10	110	131.78	6.33	54.43	1.04
12/31/10	113	129.70	11.51	52.73	0.67
1/3/11	116	254.95	7.19	20.56	0.21
1/5/11	118	273.00	2.28	25.25	1.41
1/7/11	120	297.53	7.98	27.75	0.35
1/10/11	123	296.75	6.32	32.61	0.94
1/12/11	125	304.00	5.58	48.10	0.57
1/14/11	127	289.80	2.54	43.33	0.09
1/17/11	130	137.38	2.53	17.96	0.29
1/18/11	131	257.50	8.32	16.39	4.55
1/21/11	134	300.33	2.72	3.75	0.13
1/24/11	137	251.60	2.08	10.80	1.31
1/26/11	139	244.10	7.10	9.92	0.12
1/28/11	141	365.40	0.28	41.83	2.30
1/31/11	144	532.90	5.48	40.91	1.64
2/2/11	146	608.00	2.90	114.94	1.51
2/4/11	148	669.60	9.89	249.19	83.66
2/11/11	155	720.88	76.84	134.63	1.53
2/14/11	158	622.00	85.44	164.00	56.47
2/17/11	161	660.38	7.90	140.19	1.14
2/18/11	162	701.50	16.17	122.06	0.90
2/21/11	165	779.25	6.26	59.39	1.04
2/23/11	167	776.20	3.17	96.06	0.54

Table O2 (Cont.) - Average measured NO_3^--N in pilot scale N tank and D tank.

Date	Day	N Tank mg-N/L	N Tank Std Dev	D Tank mg-N/L	D Tank Std Dev
2/25/11	169	740.50	0.60	114.10	0.36
2/28/11	172	683.05	5.92	63.48	0.68
3/3/11	175	689.63	10.02	40.40	0.90
3/5/11	177	642.38	13.46	61.84	0.72
3/7/11	179	585.50	6.76	32.14	0.68
3/9/11	181	577.38	9.33	32.65	0.46
3/11/11	183	676.63	69.80	62.39	1.27
3/14/11	186	580.38	6.42	11.00	0.17
3/16/11	188	621.50	13.27	16.01	0.34
3/21/11	193	615.38	7.40	7.01	0.29
3/25/11	197	535.13	16.03	28.05	0.61
3/30/11	202	527.13	5.09	13.55	2.96
4/1/11	204	450.44	3.40	0.22	0.32
4/4/11	207	549.00	13.43	-0.13	0.06
4/6/11	209	547.06	8.36	-0.52	0.21
4/8/11	211	537.38	3.44	-0.53	0.15
4/11/11	214	538.38	1.76	-0.67	0.03
4/13/11	216	522.81	3.51	-0.73	0.02
4/15/11	218	499.25	5.03	49.61	0.69
4/18/11	221	510.00	8.09	17.43	0.17
4/20/11	223	516.13	3.89	-0.24	0.30
4/25/11	228	436.50	4.10	16.80	0.12
4/27/11	230	493.88	5.34	7.18	0.15
4/29/11	232	463.13	1.83	-1.29	0.06
5/2/11	235	439.31	5.68	1.01	0.10
5/4/11	237	424.13	3.33	-0.86	0.53
5/6/11	239	422.75	4.30	31.23	1.85
5/9/11	242	392.94	0.99	17.99	4.53
5/11/11	244	363.21	5.75	2.36	0.14
5/13/11	246	263.38	2.99	-0.44	0.13
5/18/11	251	13.81	1.20	-0.63	0.30
AVERAGE		**411.98**		**132.94**	
Std. Dev.		**239.47**		**187.33**	

Table O3- Average measured NO_3^--N in pilot scale N tank and D tank.

Date	Day	N Tank		D Tank	
		mg-N/l	Std Dev	mg-N/l	Std Dev
9/10/10	1	-6.0	14.5	-11.5	57.6
9/11/10	2	25.0	11.0	-0.6	24.0
9/13/10	4	51.1	19.1	30.7	16.4
9/14/10	5	17.6	36.4	13.3	4.0
9/16/10	7	36.3	45.0	27.6	16.5
9/18/10	9	27.6	53.9	28.0	25.1
9/19/10	10	6.1	15.9	31.8	28.1
9/23/10	14	51.4	43.3	48.1	19.9
9/26/10	17	142.5	9.2	85.5	21.1
9/27/10	18	132.9	38.6	75.6	26.3
9/29/10	20	129.8	26.0	109.1	12.9
10/1/10	22	176.9	30.7	154.5	38.0
10/4/10	25	179.8	15.4	154.0	83.2
10/6/10	27	176.2	26.6	134.5	6.7
10/8/10	29	177.2	35.1	133.1	15.6
10/11/10	32	170.1	10.6	145.6	28.6
10/13/10	34	163.0	6.4	143.9	30.4
10/15/10	36	201.1	23.0	144.5	67.3
10/18/10	39	201.1	17.4	121.6	70.0
10/22/10	43	361.7	46.6	183.4	8.4
10/25/10	46	504.8	22.1	249.7	29.5
10/27/10	48	566.7	44.5	309.6	11.5
10/29/10	50	731.3	6.2	361.1	11.7
11/1/10	53	1,155.8	32.3	558.9	28.3
11/3/10	55	1,109.5	3.3	657.3	14.5
11/5/10	57	1,012.4	5.9	733.6	13.8
11/8/10	60	956.5	47.4	609.6	10.8
11/10/10	62	888.3	18.4	613.9	50.1
11/12/10	64	854.5	12.1	642.0	21.0
11/15/10	67	784.5	7.8	667.7	42.0
11/17/10	69	731.8	5.1	648.6	21.5
11/19/10	71	926.9	51.6	694.2	4.1
11/22/10	74	887.6	128.7	677.2	26.3
11/24/10	76	821.6	34.0	594.0	56.2
11/29/10	81	968.7	156.4	641.4	28.6
12/1/10	83	984.9	22.3	685.2	12.7
12/3/10	85	844.7	96.6	688.5	20.2
12/6/10	88	992.3	61.4	645.3	70.3
12/10/10	92	1,012.9	53.0	356.5	21.0
12/13/10	95	1,027.6	31.7	40.3	7.2
12/15/10	97	1,094.4	7.9	-4.2	1.1
12/17/10	99	1,445.1	165.1	308.5	20.3
12/20/10	102	1,094.8	6.9	518.0	4.7
12/23/10	105	1,127.1	36.7	545.7	52.6
12/25/10	107	1,150.2	134.6	700.8	5.5

Table O3 (Cont.) - Average measured NO_3^--N in pilot scale N tank and D tank.

Date	Day	N Tank		D Tank	
		mg-N/l	Std Dev	mg-N/l	Std Dev
12/28/10	110	1,228.8	28.6	673.3	11.3
12/31/10	113	1,027.9	113.7	648.7	2.8
1/3/11	116	743.6	48.0	598.2	24.6
1/5/11	118	851.2	50.3	572.1	2.1
1/7/11	120	875.8	13.5	593.5	32.7
1/10/11	123	1,006.8	131.2	564.7	10.1
1/12/11	125	864.4	78.0	540.7	4.9
1/14/11	127	787.2	17.9	505.7	23.3
1/17/11	130	536.2	7.0	458.1	7.2
1/18/11	131	688.4	15.1	483.7	6.1
1/21/11	134	604.7	8.2	397.0	3.5
1/24/11	137	596.7	5.7	316.8	6.5
1/26/11	139	371.3	23.5	220.8	1.0
1/28/11	141	464.9	109.2	259.2	2.5
1/31/11	144	449.6	33.5	230.4	1.8
2/2/11	146	360.9	8.4	200.1	2.2
2/4/11	148	222.2	166.1	166.1	104.3
2/11/11	155	417.5	136.1	193.4	18.9
2/14/11	158	360.5	158.2	181.3	59.9
2/17/11	161	346.3	10.1	147.4	3.5
2/18/11	162	341.2	22.9	124.3	2.1
2/21/11	165	349.0	15.7	120.5	9.8
2/23/11	167	325.6	7.6	223.7	2.9
2/25/11	169	361.3	66.1	249.4	3.0
2/28/11	172	289.2	9.1	164.3	1.7
3/3/11	175	248.2	74.0	80.8	11.6
3/5/11	177	163.1	9.3	60.8	3.1
3/7/11	179	344.8	10.0	156.4	3.1
3/9/11	181	315.3	20.3	137.1	4.4
3/11/11	183	341.7	124.8	162.2	4.1
3/14/11	186	232.6	70.1	35.3	1.5
3/16/11	188	167.6	9.9	32.5	2.1
3/21/11	193	144.5	11.3	19.8	1.0
3/25/11	197	212.3	3.7	15.5	0.7
3/30/11	202	123.5	15.4	4.3	3.9
4/1/11	204	113.2	4.9	-4.2	0.3
4/4/11	207	119.2	9.5	-3.9	0.1
4/6/11	209	144.7	9.4	-2.1	0.3
4/8/11	211	149.6	3.8	-2.0	0.2
4/11/11	214	143.5	2.9	-2.2	0.1
4/13/11	216	98.0	7.3	0.4	0.1
4/15/11	218	145.1	15.3	17.2	0.9
4/18/11	221	107.4	11.8	4.1	0.3
4/20/11	223	86.8	6.5	0.1	0.4
4/25/11	228	136.8	7.6	5.1	0.5
4/27/11	230	66.0	13.9	1.2	0.3

Table O3 (Cont.) - Average measured NO_3^--N in pilot scale N tank and D tank.

Date	Day	N Tank		D Tank	
		mg-N/l	Std Dev	mg-N/l	Std Dev
4/29/11	232	87.3	4.2	-0.7	0.1
5/2/11	235	97.8	9.3	-0.2	0.1
5/4/11	237	105.9	6.2	4.1	0.6
5/6/11	239	97.0	9.0	12.8	3.0
5/9/11	242	150.1	6.8	19.1	5.0
5/11/11	244	281.7	13.6	26.2	0.9
5/13/11	246	328.4	8.3	23.9	0.7
5/18/11	251	649.3	6.6	136.8	1.5
AVERAGE		**464.3**		**249.2**	
Std. Dev.		**379.3**		**249.6**	

Table O4 - Average measured TN and TDN in the pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Total Nitrogen						Total Dissolved Nitrogen					
		Lagoon Effluent		N Tank		D Tank		Lagoon Effluent		N Tank		D Tank	
		mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev
11/22/10	73	2,606.5	298.9	1,041.5	71.4	1,304.6	32.1	2,430.5	16.6	1,055.8	25.3	1,238.7	43.8
11/24/10	75	2,728.5	247.6	1,046.3	33.6	1,193.4	25.4	2,519.5	122.7	1,018.5	16.3	1,236.5	57.9
11/29/10	80	2,859.5	60.7	932.3	23.1	1,177.8	68.0	2,435.5	112.9	989.3	60.3	1,174.9	50.8
12/1/10	82	2,784.4	182.0	932.5	46.1	1,153.6	47.5	2,405.0	146.2	840.2	26.5	1,134.1	33.7
12/3/10	84	3,064.0	16.6	1,026.0	173.7	1,269.4	94.0	2,458.8	98.9	847.2	42.2	1,129.5	38.9
12/6/10	87	3,737.6	700.1	1,377.1	334.7	1,203.9	53.8	2,670.0	41.0	936.9	36.7	1,143.7	34.2
12/10/10	91	2,289.5	15.4	944.3	65.3	1,467.7	41.8	1,634.7	977.4	872.0	41.4	1,536.8	101.4
12/13/10	94	2,657.0	126.9	888.2	12.0	2,044.6	124.6	2,471.7	187.1	965.0	22.8	1,775.0	63.8
12/15/10	96	2,649.5	38.7	955.7	42.1	2,206.0	102.3	2,248.0	84.4	1,030.0	15.4	2,020.7	79.6
12/17/10	98	2,713.0	62.9	838.6	69.1	1,951.9	51.3	2,512.5	199.6	842.4	68.6	1,719.2	116.5
12/20/10	101	2,435.6	93.2	1,061.1	56.3	1,357.2	78.4	2,529.0	150.5	1,180.8	98.7	1,504.8	64.1
12/23/10	104	2,681.5	164.9	957.4	41.8	1,426.4	47.8	2,683.0	9.9	1,047.6	74.8	1,141.6	132.8
12/25/10	106	2,670.5	35.6	829.8	54.8	1,169.6	106.0	2,620.0	179.0	1,050.3	223.4	1,338.0	56.7
12/28/10	109	2,723.5	128.8	1,244.3	38.5	1,333.3	109.0	2,555.5	61.9	1,303.3	27.5	1,272.6	54.7
12/31/10	112	2,679.0	215.8	1,026.3	80.4	1,180.0	32.9	2,713.0	69.0	1,026.3	85.8	1,274.4	39.6
1/3/11	115	2,534.0	79.9	1,211.6	55.6	1,234.3	28.4	2,620.8	86.7	2,000.0	93.3	1,252.5	59.5
1/5/11	117	2,622.5	76.1	1,208.4	39.2	1,312.9	17.5	2,713.5	110.2	1,240.1	36.2	1,331.5	63.7
1/7/11	119	2,474.5	107.6	1,116.3	63.3	1,298.1	53.0	2,656.5	21.0	1,241.6	53.6	1,314.8	26.6
1/10/11	122	2,384.0	79.3	1,167.8	24.1	1,262.8	20.9	2,545.5	38.9	1,188.1	44.1	1,252.7	63.8
1/12/11	124	2,465.5	158.4	1,258.7	106.4	1,443.2	159.0	2,715.0	94.7	1,207.9	91.4	1,289.2	26.7
1/14/11	126	2,724.0	30.8	1,068.9	62.3	1,204.9	21.0	2,603.6	80.0	1,109.0	26.6	1,178.8	32.5
1/17/11	129	2,813.2	60.4	1,309.6	22.1	1,213.7	52.8	2,514.4	51.4	1,114.3	37.9	1,171.9	79.6
1/18/11	130	2,721.0	33.6	1,104.4	40.5	1,272.1	35.6	2,748.5	47.1	1,155.5	48.3	1,315.4	121.1
1/21/11	133	2,774.5	101.4	1,277.2	46.0	1,314.2	29.8	2,554.8	78.7	1,246.1	17.8	1,317.1	79.7
1/24/11	136	2,774.0	22.0	1,234.3	32.3	1,364.6	61.5	2,467.6	68.7	1,140.6	33.4	1,360.5	61.1
1/26/11	138	2,672.5	23.6	1,261.8	40.8	1,342.1	24.0	2,786.0	238.2	1,321.4	40.4	1,336.3	45.7
1/28/11	140	2,774.4	97.7	1,251.8	27.1	1,324.3	37.3	2,613.0	66.7	1,356.9	74.7	1,227.6	26.7

Table O4 (Cont.) - Average measured TN and TDN in the pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Total Nitrogen						Total Dissolved Nitrogen					
		Lagoon Effluent		N Tank		D Tank		Lagoon Effluent		N Tank		D Tank	
		mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev	mg-N/L	Std Dev
1/31/11	143	2,639.5	62.3	1,129.8	65.9	1,209.7	29.5	2,570.0	85.5	1,293.5	18.1	1,222.5	14.0
2/2/11	145	2,867.5	25.2	1,036.5	15.0	1,276.8	28.8	2,750.0	111.3	1,138.5	56.2	1,291.3	24.2
2/4/11	147	2,745.0	206.0	1,099.2	17.7	1,221.3	29.1	2,639.0	83.9	1,114.3	21.4	1,199.0	46.1
2/7/11	150	2,731.0	51.6	1,015.3	6.4	1,201.0	19.4	2,494.0	190.4	1,093.4	31.5	1,218.0	23.8
2/9/11	152	2,836.0	91.9	1,117.0	26.3	1,211.3	30.8	2,799.0	141.7	1,119.5	12.3	1,227.0	14.4
2/11/11	154	2,768.5	100.2	1,078.5	31.4	1,180.8	14.4	2,757.2	76.7	1,088.0	11.7	1,163.0	26.4
2/14/11	157	2,739.5	162.5	1,083.6	28.4	1,248.0	39.3	2,529.6	92.4	1,079.0	43.1	1,175.8	2.9
2/17/11	160	2,784.0	219.8	1,022.3	8.3	1,117.0	44.1	2,792.0	28.1	1,065.5	8.1	1,128.8	6.4
2/18/11	161	2,924.5	83.6	1,018.5	8.5	1,157.8	16.5	2,804.0	77.5	1,016.9	23.0	1,083.8	50.6
2/21/11	164	2,826.4	131.7	964.4	32.5	1,043.5	9.3	2,853.5	134.0	1,011.3	15.5	1,050.5	13.0
2/23/11	166	2,946.0	194.3	980.9	13.0	1,041.5	18.0	2,737.5	36.5	916.2	39.0	998.5	12.3
2/25/11	168	2,938.5	186.9	979.9	7.8	1,030.2	24.5	2,731.0	69.1	939.3	27.4	968.0	18.7
2/28/11	171	2,894.4	174.0	836.9	13.0	988.4	135.0	2,751.0	163.2	859.6	19.6	934.6	33.1
3/3/11	174	2,787.2	273.0	868.2	36.7	908.0	25.2	2,620.0	89.1	819.7	10.3	890.0	22.3
3/5/11	176	2,906.0	139.5	814.4	15.4	917.0	46.2	2,768.5	37.3	841.2	26.6	857.3	34.0
3/7/11	178	2,728.5	119.7	795.8	15.7	881.7	23.0	2,712.3	179.3	769.1	24.0	812.1	60.4
3/9/11	180	2,821.0	76.9	759.9	37.5	855.1	18.9	2,601.5	101.1	705.3	9.6	791.6	20.6
3/11/11	182	2,591.0	236.8	689.4	15.0	818.9	11.8	2,854.0	206.6	737.9	9.8	787.4	38.5
3/14/11	185	2,607.0	31.4	666.9	15.1	775.6	50.6	2,686.5	57.4	684.2	14.5	749.0	40.7
3/16/11	187	2,729.0	77.7	690.3	18.1	773.2	23.1	2,808.0	120.6	673.2	19.6	752.5	15.2
3/21/11	192	2,832.0	93.3	664.6	12.8	795.3	7.4	2,685.0	84.4	611.6	21.4	655.5	26.1
3/25/11	196	2,686.5	209.0	586.1	17.0	677.0	8.2	2,658.3	88.1	633.0	30.5	711.4	14.4
3/30/11	201	2,667.0	142.3	618.2	39.7	787.7	28.6	2,803.0	171.0	612.6	8.5	747.8	14.8
4/1/11	203	2,851.5	211.5	641.8	50.0	760.9	25.6			632.8	25.4	711.9	18.5
4/4/11	206	3,202.5	140.0	582.5	24.1	777.0	15.6	2,982.0	70.3	591.5	11.0	739.9	13.9
4/6/11	208	3,083.5	44.8	593.9	13.0	770.2	6.9						
AVERAGE		**2,757.5**		**979.4**		**1,178.3**		**2,623.8**		**1,007.2**		**1,151.1**	
Std. Dev.		**215.2**		**209.4**		**304.4**		**199.1**		**249.8**		**281.3**	

Table O5 - Average measured COD in pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Lagoon Effluent				N Tank				D Tank			
		Soluble		Total		Soluble		Total		Soluble		Total	
		mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev
9/13/10	3					788.6	30.4	888.6	10.1	895.7	20.2	1,210.0	0.0
9/15/10	5					767.0	0.0	881.0	20.5	853.0	19.8	1,117.0	9.9
9/27/10	17	1,385.0	0.0	1,772.5	17.7	1,373.0	17.7	1,760.0	0.0	3,335.0	70.7	4,772.5	17.7
9/29/10	19	3,378.0	17.7	4,740.0	0.0	1,360.0	0.0	1,847.5	17.7	1,440.0	35.4	1,790.0	70.7
10/1/10	21					1,533.0	106.1						
10/4/10	24	3,733.0	35.4	5,483.0	212.1	1,445.5	17.7			1,733.0	35.4		
10/6/10	26					1,558.0	70.7						
10/11/10	31	3,378.0	17.7	5,115.0	35.4	1,740.0	35.4	2,090.0	0.0	2,040.0	0.0	2,540.0	0.0
10/15/10	35					1,355.0	0.0	1,918.0	17.7	1,493.0	17.7	2,330.0	35.4
10/18/10	38	3,300.0	70.7	4,813.0	53.0	1,775.0	0.0	2,350.0	0.0	1,888.0	17.7	2,475.0	35.4
10/22/10	42					1,975.0	106.1	2,500.0	0.0	2,020.0	0.0	2,808.0	17.7
10/24/10	44					1,080.0	17.7	2,255.0	88.4	1,443.0	0.0	2,105.0	53.0
10/25/10	45	1,938.0	17.7	2,900.0	35.4	1,763.0	17.7	2,500.0	35.4	1,838.0	17.7	2,775.0	35.4
10/27/10	47					1,750.0	17.7	2,538.0	35.4	1,975.0	17.7	2,838.0	106.1
10/29/10	49	3,325.0	17.7	4,900.0	53.0	1,425.0	17.7	2,088.0	0.0	1,800.0	17.7	2,900.0	17.7
11/10/10	61	3,158.0	17.7	4,783.0	17.7	1,333.0	17.7	1,908.0	17.7	1,683.0	88.4	2,395.0	35.4
11/17/10	68	3,243.0	17.7	4,668.0	17.7	1,455.0	35.4	2,105.0	35.4	1,493.0	17.7	2,205.0	0.0
11/29/10	80	3,355.0	17.7	5,180.0	17.7	955.0	17.7	1,280.0	17.7	1,343.0	0.0	1,880.0	17.7
12/1/10	82									1,438.0	0.0	2,075.0	17.7
12/3/10	84					988.0	35.4	1,750.0	17.7	1,363.0	0.0	2,525.0	17.7
12/6/10	87					900.0	17.7	1,500.0	17.7	1,363.0	35.4	2,225.0	17.7
12/10/10	91					895.0	17.7	1,545.0	17.7	1,983.0	35.4	3,183.0	35.4
12/13/10	94	4,033.0	35.4	5,708.0	0.0	908.0	0.0	1,670.0	53.0	2,495.0	17.7	3,970.0	17.7
12/17/10	98					968.0	35.4	1,530.0	17.7	2,468.0	35.4	3,605.0	17.7
12/20/10	101	4,430.0	17.7	6,130.0	17.7	1,230.0	17.7	2,143.0	35.4	1,880.0	17.7	3,043.0	70.7
1/3/11	115					1,605.0	0.0	2,143.0	17.7	1,693.0	17.7	2,155.0	0.0
1/5/11	117	5,245.0	17.7	7,020.0	53.0	1,770.0	17.7	2,783.0	70.7	1,920.0	17.7	2,595.0	17.7
1/7/11	119					1,705.0	17.7	3,180.0	88.4	1,780.0	17.7	2,468.0	0.0
1/10/11	122	5,143.0	35.4	6,955.0	123.7	1,755.0	17.7	2,405.0	53.0	1,768.0	0.0	2,793.0	0.0

Table O5 (Cont.) - Average measured COD in pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Lagoon Effluent				N Tank				D Tank			
		Soluble		Total		Soluble		Total		Soluble		Total	
		mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev
1/14/11	126					1,932.5	17.7	2,907.5	88.4	1,982.5	53.0	3,370.0	35.4
1/17/11	129	5,420.0	70.7	7,245.0	106.1	2,007.5	17.7	2,970.0	35.4	1,982.5	53.0	3,070.0	35.4
1/24/11	136					1,920.5	17.7	3,395.5	88.4	2,258.0	35.4	2,983.0	35.4
1/26/11	138	6,070.5	17.7	7,995.5	17.7	1,995.5	17.7	3,008.0	0.0	2,183.0	0.0	3,033.0	0.0
1/31/11	143					2,333.0	0.0	4,070.5	194.5	2,195.5	17.7	3,008.0	0.0
2/2/11	145	6,258.0	35.4	7,908.0	35.4	2,520.5	53.0	3,158.0	35.4	2,283.0	35.4	2,933.0	35.4
2/7/11	150					2,545.0	0.0	3,307.5	53.0	2,357.5	17.7	3,157.5	17.7
2/9/11	152	6,420.0	35.4	8,445.0	35.4	2,557.5	17.7	3,120.0	35.4	2,320.0	70.7	2,907.5	17.7
2/11/11	154					2,630.0	0.0	3,805.0	35.4	2,417.5	17.7	3,317.5	88.4
2/14/11	157	6,742.5	17.7	8,655.0	0.0	2,517.5	17.7	3,230.0	0.0	2,367.5	17.7	3,155.0	0.0
2/21/11	164					2,943.0	35.4	3,880.5	53.0	2,355.5	17.7	3,268.0	70.7
2/23/11	166	7,330.5	53.0	9,268.0	35.4	2,905.5	17.7	3,380.5	17.7	2,468.0	0.0	3,068.0	0.0
2/28/11	171	7,188.0	0.0	9,038.0	0.0	2,663.0	35.4	3,013.0	0.0	2,363.0	0.0	3,213.0	353.6
3/3/11	174	7,405.0	35.4	9,334.0	65.1	2,555.0	35.4	2,880.0	35.4	2,280.0	0.0	2,855.0	35.4
3/5/11	176					2,254.0	0.0			2,114.0	0.0		
3/7/11	178					2,445.0	35.4	2,620.0	106.1	2,257.5	17.7	2,807.5	17.7
3/9/11	180	7,232.5	17.7	9,332.5	17.7	2,482.5	17.7	2,670.0	0.0	2,320.0	0.0	2,882.5	53.0
3/11/11	182									1,897.3	227.2	2,257.3	104.6
3/14/11	185					2,580.0	0.0	3,230.0	0.0	2,355.0	35.4	2,880.0	35.4
3/16/11	187	7,355.0	106.1	9,567.5	17.7	2,642.5	17.7	2,642.5	17.7	2,342.5	17.7	2,992.5	17.7
3/21/11	192									2,263.0	35.4	2,988.0	0.0
3/24/11	195									2,188.0	27.4	2,346.3	20.4
3/25/11	196					2,563.0	35.4	4,675.5	17.7				
3/30/11	201	7,317.5	17.7	9,542.5	53.0	2,592.5	17.7	3,180.0	0.0	2,417.5	53.0	3,105.0	70.7
4/1/11	203					2,657.5	17.7	3,320.0	35.4	2,445.0	0.0	3,257.5	17.7
4/4/11	206	7,711.5	12.0	10,007.5	17.7	2,620.0	0.0	2,957.5	17.7	2,445.0	0.0	3,107.5	17.7
4/6/11	208	7,575.0	17.7	10,069.0	26.9	2,513.0	0.0	3,100.5	17.7	2,450.5	53.0	3,300.5	53.0
4/8/11	210	7,313.0	70.7	10,200.5	17.7	2,420.0	35.4	3,145.0	35.4	2,332.5	17.7	3,220.0	0.0
4/11/11	213					2,457.5	17.7	3,257.5	17.7	2,332.5	17.7	3,282.5	17.7

Table O5 (Cont.) - Average measured COD in pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Lagoon Effluent				N Tank				D Tank			
		Soluble		Total		Soluble		Total		Soluble		Total	
		mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev	mg COD/L	Std Dev
4/13/11	215	6,925.5	17.7	9,913.0	212.1	2,225.5	17.7	2,888.0	35.4	2,125.5	17.7	3,125.5	17.7
4/15/11	217					2,408.0	35.4	3,120.5	17.7	2,270.5	17.7	3,045.5	53.0
4/18/11	220	6,838.0	70.7	9,788.0	176.8	2,500.5	17.7	2,944.0	114.6	2,288.0	0.0	3,225.5	17.7
4/20/11	222	6,545.5	17.7	9,495.5	17.7	2,445.5	17.7	3,120.5	17.7	2,245.5	17.7	2,970.5	17.7
4/25/11	227			9,583.0	70.7	2,220.5	53.0	3,858.0	0.0	2,108.0	0.0	2,858.0	35.4
4/27/11	229					2,382.5	17.7	2,945.0	0.0	2,132.5	17.7	3,220.0	35.4
5/2/11	234	5,970.0	0.0	9,795.0	106.1	2,320.0	35.4	2,870.0	35.4	2,145.0	0.0	3,082.5	17.7
5/6/11	238	5,295.0	70.7	9,107.5	17.7	2,182.5	17.7	2,757.5	17.7	1,970.0	35.4	2,995.0	0.0
5/9/11	241					2,132.5	17.7	2,745.0	0.0	2,007.5	17.7	3,582.5	17.7
5/13/11	245	4,968.0	0.0	8,880.5	17.7	2,093.0	0.0	2,780.5	53.0	2,193.0	0.0	3,418.0	0.0
5/16/11	248					1,800.0	0.0	2,825.0	35.4	2,025.0	0.0	2,950.0	0.0
5/20/11	252	4,137.5	53.0	7,612.5	53.0	1,675.0	35.4	3,587.5	53.0	1,950.0	0.0	2,600.0	35.4
5/23/11	255					1,713.0	35.4	3,988.0	671.8	1,925.5	17.7	2,975.5	17.7
5/25/11	257	3,900.5	17.7	7,413.0	141.4	1,613.0	35.4	3,238.0	0.0	1,888.0	70.7	2,713.0	0.0
AVERAGE		**5,304.5**		**7,523.3**		**1,942.9**		**2,721.1**		**2,038.7**		**2,855.3**	
Std. Dev.		**1,803.5**		**2,263.2**		**592.5**		**766.4**		**402.9**		**564.1**	

Table O6 - Measured alkalinity in pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Lagoon Effluent		N Tank		D Tank	
		Bicarbonate	Total	Bicarbonate	Total	Bicarbonate	Total
		mg CaCO3/L	mg CaCO3/L	mg CaCO3/L	mg CaCO3/L	mg CaCO3/L	mg CaCO3/L
09/27/10	17	11,210	11,875	546	713		
10/05/10	25	11,139	12,136	285	523	2,138	2,636
10/12/10	32	10,308	11,353	974	1,069	2,660	2,708
10/15/10	35	11,281	12,113	950	1,473	2,993	3,729
10/27/10	47	11,156	12,206	1,181	1,811	3,885	4,725
11/03/10	54	11,025	11,944	1,706	2,389	3,544	4,331
11/10/10	61	11,156	11,813	2,625	3,281	4,200	4,988
11/19/10	70	10,894	11,813	1,444	2,100	4,095	4,883
12/06/10	87			1,444	2,231	4,594	5,250
12/15/10	96	10,894	12,075	3,413	3,990	10,631	11,419
12/23/10	104	10,631	12,075	4,200	4,988	6,694	7,481
12/30/10	111	10,763	12,206	4,200	5,119	6,038	7,219
01/05/11	117	10,631	12,259	3,806	4,725	6,431	7,219
01/18/11	130	10,316	12,128	4,331	5,775	6,956	8,006
02/01/11	144	10,763	12,600	3,885	4,856	7,350	8,400
02/17/11	160	10,238	12,206	3,150	4,069	7,088	8,006
02/18/11	161	10,369	12,338	3,150	3,938	7,219	8,006
03/04/11	175	10,763	13,073	2,704	3,596	6,956	7,875
03/09/11	180	10,238	12,469	2,888	3,806	6,694	7,613
04/12/11	214	9,844	12,338	2,494	3,413	6,431	7,350
04/18/11	220	10,238	12,416	2,888	3,728	6,169	6,956
04/21/11	223	9,975	12,206	3,019	3,806	6,431	7,140
04/27/11	229	10,054	12,338	2,494	3,754	5,513	6,694
05/03/11	235	9,844	11,183	2,363	3,544	5,775	6,904
05/06/11	238	10,106	12,731	2,231	3,203	5,119	6,563
05/11/11	243	10,106	12,731			2,231	3,203
05/18/11	250	10,106	12,731	1,575	2,625	4,856	6,169
05/26/11	258	11,025	12,731	1,181	2,231	5,171	6,746
AVERAGE		**10,558**	**12,225**	**2,412**	**3,213**	**5,476**	**6,378**
Std. Dev.		**460**	**415**	**1,170**	**1,373**	**1,898**	**1,993**

Table O7 - Average measured total suspended solids and volatile suspended solids in the pilot scale lagoon effluent, N tank, and D tank.

Date	Day	Lagoon Effluent						N Tank						D Tank					
		TSS		VSS		VSS/TSS		TSS		VSS		VSS/TSS		TSS		VSS		VSS/TSS	
		(mg TSS/ L)	Std Dev	(mg TSS/ L)	Std Dev	Avg. VSS/ TSS	Std Dev	(mg TSS/ L)	Std Dev	(mg TSS/ L)	Std Dev	Avg. VSS /TSS	Std Dev	(mg TSS/ L)	Std Dev	(mg TSS/ L)	Std Dev	Avg. VSS /TSS	Std Dev
10/15/10	35	1,458	47					814	10					718	25				
10/27/10	47	1,532	135					1,289	106					1,029	10				
11/01/10	52	1,360	792					1,470	198					893	10				
11/03/10	54	1,680	0					1,164	0					1,050	0				
11/11/10	62	1,179	29					685	28					650	35				
11/17/10	68	1,186	20					1,003	14					840	0				
11/19/10	70	1,367	9					1,815	21					879	48				
12/06/10	87	1,443	33					694	8					1,555	120				
12/15/10	96	1,410	5					845	21					1,353	38				
01/05/11	117	1,940	14					2,420	170					835	0				
01/07/11	119	2,180	339					2,630	198					1,120	47				
01/12/11	124	1,637	19					3,018	371					922	13				
01/14/11	126	1,626	404	686	311	0.41	0.52	1,213	11	487	52	0.40	0.11	1,456	244	646	147	0.44	0.28
01/17/11	129	1,233	11	502	172	0.41	0.34	988	54	378	1	0.38	0.05	1,178	192	527	88	0.45	0.23
01/21/11	133	1,394	0	549	0	0.39	0.00	912	27	354	26	0.39	0.08	753	66	310	24	0.41	0.12
01/24/11	136	1,580	14	645	35	0.41	0.06	1,235	122	524	57	0.42	0.15	959	48	452	2	0.47	0.05
01/28/11	140	2,051	137	790	51	0.39	0.09	1,348	12	602	25	0.45	0.04	1,119	14	564	13	0.50	0.03
01/31/11	143	1,421	41	521	29	0.37	0.06	1,467	152	551	128	0.37	0.26	687	0	400	0	0.58	0.00
02/04/11	147	1,616	23	647	94	0.40	0.15	1,220	57	440	28	0.36	0.08	798	29	357	28	0.45	0.09
02/09/11	152	1,960	184	770	57	0.40	0.12	1,588	100	646	65	0.41	0.12	1,047	170	457	33	0.44	0.18
02/11/11	154	1,716	150	622	11	0.36	0.09	1,334	113	477	3	0.36	0.08	910	108	400	38	0.44	0.15
02/14/11	157	1,700	0	620	14	0.36	0.02	1,052	27	392	13	0.37	0.04	1,113	179	465	59	0.42	0.20
02/21/11	164	1,605	21	575	35	0.36	0.06	1,258	70	531	32	0.42	0.08	1,090	33	470	33	0.43	0.08
02/25/11	168	1,365	35	570	14	0.42	0.04	641	14	244	3	0.38	0.03	924	13	423	25	0.46	0.06
03/03/11	174	1,520	28	780	71	0.51	0.09	477	32	187	11	0.39	0.09	934	65	481	40	0.52	0.11
03/11/11	182	1,885	7	640	14	0.34	0.02	398	11	215	7	0.54	0.04	960	35	486	42	0.51	0.09
03/16/11	187	1,515	445	655	35	0.46	0.30	675	85	313	11	0.47	0.13	742	44	417	6	0.56	0.06
AVERAGE		1,576		638		0.40		1,246		423		0.41		982		457		0.47	
Std. Dev.		256		90		0.04		628		141		0.05		223		82		0.05	